NASA-TM-109724

7N 12-TM
32 17
180 P

PROCEEDINGS OF THE

SPACE STATION EVOLUTION WORKSHOP

WILLIAMSBURG, VIRGINIA

JULY 29 - AUGUST 1, 1986

(NASA-TM-109724) PROCEEDINGS OF THE SPACE STATION EVOLUTION WORKSHOP (NASA) 180 p

N94-71729

Unclas

Z9/18 0002379

OFFICE OF SPACE STATION
NASA HEADQUARTERS
WASHINGTON, DC

TABLE OF CONTENTS

PAGE II

INDEX OF EXHIBITS

INTRODUCTION

~~PAGE INTENTIONALLY BLANK~~

INTRODUCTION

The Space Station Program is different from previous NASA programs in at least two respects: (1) the Space Station's indefinite operational lifetime and (2) the plans to expand the capacities and capabilities of the Space Station on orbit. The increases in capacities and capabilities will occur in a series of steps, some incremental, others major expansions. The scope of the evolution program encompasses planning for all these steps and ensures that the baseline Space Station is designed to accommodate future changes.

Two Space Station Evolution Workshops have been held to develop a better understanding of requirements for the evolution phases. The first workshop was held September 10 through 13, 1985, with participants from NASA only. At that workshop, NASA began looking beyond the Space Station's 10-year user mission data set to a broader scope of evolution. Under this wider scope, the participants considered the potential impacts of expanded commercial requirements and of recommendations from the National Commission on Space.

The results of the 1985 workshop are summarized in the report, "Proceedings of the Space Station Evolution Workshop, Hilton National Conference Center, Williamsburg, Virginia, September 10-13, 1985." A major finding of this workshop was that "branching" is likely to be a major evolution mode. Certain sets of user functions will be transferred to a replicated manned base or platform to avoid operational conflicts as the number and types of users increase.

The second Space Station Evolution Workshop, held July 29 through August 1, 1986, in Williamsburg, expanded the work of the first workshop by including participants from other government agencies, the international community, industry, and universities as well as from NASA. The objectives of the workshop were (1) to develop concepts for the evolution of the Space Station to meet user needs; (2) to identify major mission and system issues associated with evolution planning; and (3) to identify evolution technology needs. This document is the summary report of the second workshop.

The workshop consisted of five discipline teams and two synthesis teams. A list of participants and their team support is provided as Appendix A. The discipline teams -- astrophysics, communications, Earth observations, lunar and planetary missions, and microgravity -- identified requirements, issues, and infrastructure concepts in their areas of interest. The concept synthesis team integrated the mission requirements, issues, and infrastructure concepts to form a unified set of workshop recommendations. The technology synthesis team integrated the technology requirements and recommendations. Representatives from user communities and engineering and technology disciplines were included on each team.

Three reference mission data bases were available for the workshop participants: the Space Station Mission Requirements Data Base, the Space Transportation and Support Study - Civil Needs Data Base, and the "National Commission on Space Report." In addition, some teams referred to discipline-related data bases such as the National Academy of Sciences long-range study, "Space Science 1995-2015." The teams were encouraged to compile mission models (roughly time phased) based on the reference material plus the knowledge and experience of individual team members. The teams were asked to identify the major mission and system requirements for their discipline.

The Space Station program has not established an official date for the beginning of the evolution phase. The workshop teams were instructed to assume a time frame beginning in 1995 and ending in 2035 or earlier, as appropriate for the team.

The Space Station infrastructure in place at the beginning of the evolution phases was assumed to be the dual-keel manned base with associated platforms, orbital maneuvering vehicles, communication elements, and ground systems, as defined by the Space Station Phase B studies at the time of the workshop. The teams were asked to identify concepts for evolution of the infrastructure to meet discipline needs. They were encouraged, if appropriate, to identify more than one option for acceptable infrastructure.

The teams were asked to record issues that surfaced during their discussions of the missions, requirements, and infrastructure options. They were also asked to identify studies and trades that will be needed, provisions (scars) required for the baseline Space Station to ensure orderly and efficient evolution, technologies that should be developed, and mission or system issues that should be resolved. In addition, each team devoted a major portion of its final meeting to a discussion of technology development requirements.

Information exchange among the teams was ensured by the daily plenary sessions. In addition, each team was asked to send representatives to the concept and technology synthesis team meetings, which met in parallel with the discipline teams. The synthesis teams held additional meetings when all the team summaries were completed. The synthesis results were previewed in a special workshop plenary session before being presented to NASA management.

On the last day of the workshop, a NASA management team, led by the Deputy Associate Administrator for Space Station, came to Williamsburg for a presentation of preliminary workshop results. After the workshop, an additional summary presentation was given at NASA Headquarters for the NASA General Manager, the Associate Administrator for Space Station, and Associate Administrators from other headquarters offices.

These summary presentations began NASA's review of workshop recommendations -- a process that is still under way. This report is a summary of workshop results, reviewed and updated by the workshop participants. It does not reflect any comments or decisions by NASA management or the Space Station evolution program. However, most of the workshop recommendations are expected to be incorporated in the evolution program plans as they are developed over the coming year.

In the sections of this report, the individual team chairmen and deputy chairmen document the activities and findings of their teams as reported in Williamsburg. Because of the wide range of interests represented at the workshop and because of the different ways the disciplines might use the IOC Space Station and the evolved station, each team report has its own structure and emphasis. The technical editors tried to maintain this discipline-specific aspect of the team reports. After the workshop, the final drafts were prepared and submitted to NASA. In some cases, additional data or analyses were included to fill a gap left at the workshop. The synthesis teams (concept and technology) reports may not include these post-workshop changes in their synthesized results. The results of this "delta" synthesis of concepts will be the subject of a later report.

In addition to all the participants, special recognition should be given to Pat Rawlings, who served as the workshop artist. Many of the drawings in the report that follows are his.

1. ASTRONOMY AND ASTROPHYSICS TEAM REPORT

1. ASTRONOMY AND ASTROPHYSICS TEAM REPORT

Over the first 25 years of the space program, we have seen unprecedented advances in astronomy and astrophysics, many of which have followed from observations made from space. Using instruments placed above the absorbing effects of the Earth's atmosphere, for example, we can study nearly the entire spectrum of electromagnetic and particle emissions from cosmic sources. Many discoveries would not have been possible without space-based observations:

- X-ray and infrared emitting stellar systems
- The x-ray and gamma ray cosmic background
- The properties of the interstellar medium through observations in the ultraviolet
- The existence of x-ray and infrared quasars
- The likelihood of black holes
- The gamma ray burst phenomenona
- "Star-burst" galaxies observed in the infrared
- The importance of high-energy phenomena on the sun and throughout the universe.

The second 25 years of the space program will see the completion of the "great observatories" effort begun in the 1980s and a variety of complementary activities involving the Space Shuttle, smaller free flyers, and suborbital opportunities. Many of these missions will use the Space Station in its early configuration, but other facilities will eventually be needed. The Paine Commission, recognizing the potential of continued space observations, has recommended "a sustained program to understand the evolution of the universe, through astronomical facilities of increasing power, precision, and sophistication...."*

The commission has described the new generation of space observatories needed to implement this recommendation:

- A large deployable reflector with an aperture of 65 to 150 feet for observations in the far infrared

- A large space telescope array, composed of several telescopes 25 feet in diameter that would operate in the ultraviolet, visible, and infrared spectral regions

- A set of radio telescopes 100 feet or more in diameter

- A long-baseline optical space interferometer, composed of two or more large telescopes separated by 300 miles

- A high-sensitivity x-ray facility, having about 1,000 times the collecting area of the planned advanced x-ray astrophysics facility

- A super-conducting magnet in space with 1,000 square feet of detectors, for conducting cosmic ray studies.

This team report focuses on a time when such observatories are already in place. The Space Station, which allows the development of facilities with no obvious limits on size, is the key to inaugurating this era.

---

* National Commission on Space. Pioneering the Space Frontier. Toronto: Bantam Books, 1986.

ASSUMPTIONS AT IOC

To provide a basis for evolution, an understanding of the Space Station's early configuration, capabilities, and instruments is needed. Based on available reports and plans, the team made the following assumptions on Space Station initial operating capability (IOC):

- Scientific Instruments. A number of payloads have already been defined as possible early candidates for the Space Station:
  - Cosmic-ray nuclei experiment (CRNE), a Spacelab-developed instrument adapted to the Space Station
  - High-resolution solar observatory (HRSO), a development indicated for Spacelab, but now being reconfigured for the early Space Station
  - Astrometric telescope facility (ATF), a relatively small optical telescope designed for planetary detection.

- Maintenance and Servicing. A number of payloads launched by the Shuttle or expendable launch vehicles (ELVs) have servicing requirements in the IOC time frame. These include the Hubble space telescope (HST), the gamma ray observatory (GRO), the advanced x-ray astrophysics facility (AXAF), the space infrared telescope facility (SIRTF), and Explorers.

- Payloads of Opportunity. In addition to the attached facilities, simple payloads must be accommodated at the station. These include the Space Station Spartan, the Hitchhiker, and Get-Away Specials. Many investigations can be performed with these payloads.

Station Facilities. To accommodate the scientific payloads, specific capabilities and facilities will be required. These include:

- Modules for free-flying platforms
- Two coarse-pointing control systems mounted on the Space Station truss structure
- Direct user control of and interaction with attached payloads (i.e., telescience capability)
- Servicing bay available for platforms and Explorer class spacecraft
- Orbital manuevering vehicles (OMVs) for payload retrieval and reinsertion.

The team assumed that an orbiter-based refueling capability will be available for the operating observatories at IOC. Therefore, no refueling/cryogenic replacement facilities will be available on the IOC station. This capability will be developed as part of the station evolution.

MISSION REQUIREMENTS

Many astrophysics activities in operation during or before IOC will use Space Station capabilities. Using the IOC activities as a baseline, the team identified future missions for discussion. Most of these missions, or their technical determinants, are currently under study or are recommended in various reports. The team also included in the list for discussion several missions that are likely to provide new and powerful instruments to explore the cosmos.

The team divided the facilities to accommodate these missions into two categories -- attached and platform (or free-flyer). However, it should be noted that the categories are subject to change. Facilities may evolve from attached to platform, and platforms may be attached facilities in their preliminary versions. To demonstrate the relationship of current, planned, and future missions, the team constructed a time-phased mission model that includes the IOC configuration shown on Exhibit 1-1. The properties of the facilities are summarized in Exhibits 1-2 and 1-3. Exhibit 1-4 indicates the evolution of requirements on the Space Station to accommodate these missions.

Attached facilities for astrophysics activities include the astromag, advanced solar observatory (ASO), and x-ray large array (XLA).

Astromag provides a new capability to study cosmic rays. It measures the energy, charge, and isotopic spectrum of cosmic ray nuclei in energy ranges crucial for understanding the acceleration and transport of cosmic ray particles in the galaxy. Astromag's essential component is a pair of super-conducting magnet coils confined to give a net zero magnetic moment. Each coil provides an analyzing magnetic field to determine the momentum and charge sign of cosmic rays with energies up to several hundred Bev, ranging from protons beyond iron nuclei. The use of two coils allows two experiments to be conducted simultaneously. The facility will be composed of at least three parts: the magnet assembly itself and the two experiments. Each component will require a significant part of a Shuttle bay for transport to the station for assembly.

A second attached facility, the ASO, is a cluster of instruments of unprecedented resolving power that can be used for making simultaneous observations of solar phenomena. The solar community has relied heavily on NASA space facilities, first with the Skylab cluster on ATM and more recently with the group of four instruments on the instrument point system (IPS) on Spacelab II.

EXHIBIT 1-1
SPACE STATION WITH ASTROPHYSICS
ATTACHED PLATFORMS

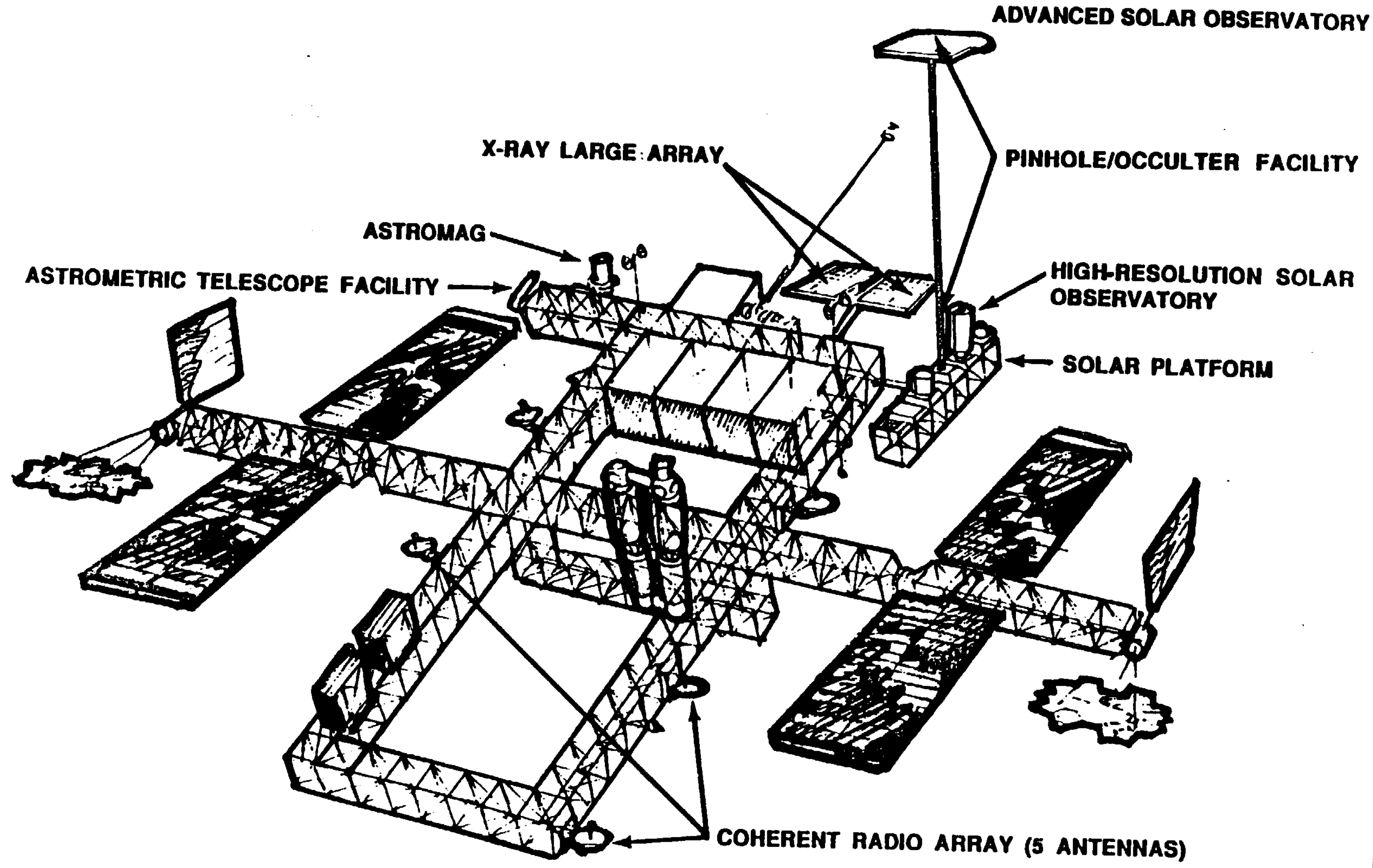


EXHIBIT 1-2
REQUIREMENTS SUMMARY: ATTACHED PAYLOADS

INSTRUMENT/ FACILITY	SIZE	DATA RATE	MOUNTING	POINTING ACCURACY	POINTING VIEW DIRECTIONS	PACKAGING	COMMENTS	DATA BASE REFERENCE
Astromag (1995)	10 x 10 X 5m		Fixed, on Upper Spar	N/A	All Sky, Above Horizon	Three Assembled Elements; superconducting Magnet, two-experiment modules	Requires ~2 years Service intervals; Experiment changeouts	SAAX 0021
Advanced Solar Observatory (1993)	10 x 50m platform	10^9BpS w/o on-board processing & storage	Solar oriented, unshadowed	~1°	Solar	Truss Type pointing mount	Assemble on Station; Attach Inst. as available	SAAX 0011
HRSO (1993)	3m dia x 10m		Solar Platform	~1° internal	Solar	Unitized Telescope/Inst. Package	Originally STS payload (SOT)	
Pinhole/ Occulter Facility (1995)	3 x 3 x 50m		Solar Platform			Occulter Deploys	Under Study	
XUV Facility (1997)			Solar Platform			Unitized Telescope/Inst. Package		
X-ray Large Array (XLA) (Initial - 1999; Full - 1994)	10 x 10 x 5m		Pointed Platform; Upper Spar	0.1°	UP; Celesial Locations	Individual modules (100); Truss material structure	Modules built-up to full configuration	

EXHIBIT 1-3
REQUIREMENTS SUMMARY:
PLATFORM PAYLOADS, ASSEMBLED

INSTRUMENT/ FACILITY	SIZE	DATA RATE	MOUNTING	POINTING ACCURACY	POINTING VIEW DIRECTIONS	PACKAGING	COMMENTS	DATA BASE REFERENCE
Large Deployable Reflector (LDR) (2005)	25 m dia x 40 m		Platform	~1"	All Sky	Mirror Segments; Focal Plane Assembly; Structure	Assembly & Checkout at Station; Deliver to Orbit	SAAX 0020
Coherent Radio Array (Initial - 1998; Complete - 2004)	200 x 200m "T" Conf.	400 MBpS w/o on-board correlation	Initial - Station Trusses; Final - Platform	~10"	Sky & Earth	37 antennas each 5m dia; Truss structure	Assemble & Checkout at Station; for Reassemble Free-flyer	-
Large Space Telescope (2005)	12m dia. x 30m lg.		Platform	1" (telescope)	All Sky	Fully Assembled; Direct Insertion to Station Orbit	Checkout & Final Configure on Station; Deploy to Operating Orbit	-
Coherent Optical Array (Interferometer) (2010)	30m dia. 60m lg. (typical)		Platform	1"	All Sky	Individual mirrors or assemblies; structure; focal plane assembly		A-NNN1

EXHIBIT 1-4
SIGNIFICANT SPACE STATION NEEDS FOR ASTRONOMY AND ASTROPHYSICS EXPERIMENTS

EXPERIMENT	MASS(Klb.)	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	NOTES
1. HST	U/D	13.2				13.2			13.2			13.2			13.2			13.2		13.2	SERVICING OF HUBBLE REFUELING EVERY 3YRS.
2. GRO	U/D					30.0					30.0		30.0			30.0			30.0		SERVICING OF GAMMA RAY.
	U	3.9		3.9																	SERVICING/CRYO EVERY 2 YRS. (other masses total 170 Klb.)
3. AXAF	U							19.0													
	CRYO. U/D									1.0		1.0		1.0		1.0		1.0		1.0	
4. SIRTF	U				8.8																SIRTF REFURBISH/SUPPLY IR OBS. (27.5 Klb. Every 2 yrs.)
	CRYO. U/D							8.8		8.8		8.8		8.8		8.8		8.8		8.8	
	U/D																			27.5	
5. NSO(ASO)																					W. TELESCIENCE DATA — 33 MBPS
HRSO(SOT)	U						26.0														+1 DEDICATED PhD CREW
P/O FAC.	U/D						6.6		6.6		6.6		6.6		6.6						INTERMITTENT SUPPLY
ADD STD.	U/D														6.6		6.6		6.6		W. TELESCIENCE
ADD EUV (ASOII)	U/D								6.6												POWER—— 2KWe. & S. THERMAL RADIATORS
6. ASTROMAG (SUPERMAG.)	U				12.6																
EQUIP. CHANGE	U/D					5.0		5.0		5.0		5.0									
LHe REPLENISH	U					4.0		4.0		4.0		4.0									
7. ATF	U	12.8																			
EQUIP CHANGE.	U/D			1.5		1.5		1.5		1.5		1.5		1.5		1.5		1.5		1.5	
8. GRIST	U										30.0										
	U/D												–			–			–		
9. COHERENT RADIO ARRAY(CRA)																					+ON-BOARD CORRELATOR
	U							5.5		5.5		5.5	3.3	227		227	20.				CRYO SUPPLY
CRYO.	U									1.0		1.0		1.0		1.0		1.0		1.0	
10. XRAY LARGE ARRAY (XLA)	U							1.0	4.0	4.0	8.0	8.0	8.0	8.0							INTERFACE W. NUCLEAR DATA—— 100KBPS POWER —— 1KWe
11. LARGE DIAM. REFLECTOR(LDR)	U														56.0						ASSEMBLE, THEN FREE FLY.
	U/D																	1.5		1.5	
12. LARGE TELESCOPE	U														TBD						FILLED APERTURE(STS) INSTRUM.+CRYO. DATA—— 100KBPS (+1KWe) POSSIBLE 100Klb to GEO?
	U/D																TBD		TBD		
13. COHERENT OPTICAL ARRAY (COA)																					80Klb. UP IN '12 1Klb. UP/DN EVERY 2 YRS. GEO-ORBIT- LOW + OTV LUNAR BASE? START IN '20 PHASED OPTICAL HETERODYNE
14. OPTICAL INTERFEROMETRY FACILITY																					2+ TELESCOPES - 100km APART
15. LARGE COSMIC/GAMMA FAC.	U														50.		20.	30.	50.	50.	+TELESCIENCE INTERFERES WITH NUCLEAR
	U/D																1.0	1.5	3.0	4.0	SUPERCOND. LHe
TOTALS	U	16.7	0.	3.9	21.3	4.0	25.0	30.1	4.0	14.5	36.0	18.5	11.3	31.0	106.[illegible]	23.	40.±	31.0	50.+	51.0	518.3 K [illegible]

NASA has identified a major new solar instrument, the HRSO, for the Space Station at IOC. This observatory will be the first of the ASO's several components. The HRSO will be capable of obtaining solar images at a 0.1-arc-second angular resolution in the visible region -- a resolution comparable to the atomic mean free path in the chromosphere. Thus, it will provide diagnostics of plasma processes in the critical region between the cool photosphere and the hot corona.

Another candidate for the ASO is the pinhole occulter facility (PO/F), which uses mechanical occulting (shadowing) techniques to achieve high angular resolution at hard x-ray and gamma-ray energies. It will be used where focusing optics are unavailable to allow coronal imaging close to the solar disc. The occulter itself will be mounted at the end of a beam, about 50 meters from the solar sensing instruments.

It is important for NASA to recognize the potential for solar observation early in the development of the Space Station and to allow for the orderly aggregation of solar instruments. A multifaceted Space-Station-based solar observatory -- perhaps operated as a national observatory -- will provide a powerful mode of studying the sun. Made up of many solar instruments operating simultaneously, this observatory will be continually provided with new instruments. A solar-oriented site on the station should be designated where individual instruments can be mounted. This area should be one that can accommodate substantial growth. The solar array arm would be almost ideal; however, an area 10 by 50 meters might eventually be needed.

A third attached facility, the XLA, will make high-sensitivity, high-energy observations of the structure, spectrum, and time variations of cosmic objects. Focusing optical systems, constructed as a series of modules, will provide high-quality information on the lower energy x-ray domain. Collimated x-ray detectors will be required for very large areas and extended energy ranges. A large array of detectors of 100 square meters and a mix of modular types would provide a facility of great power for investigating collapsed stars, active galaxies, and clusters of galaxies. Such an array could be built in modules with standard interfaces, carried into orbit, and assembled at the Space Station onto a specially constructed truss. The XLA will be a natural starting point and model for other gamma-ray and x-ray instruments, including the PO/F and a germanium gamma-ray line spectrometer.

The platform or free-flying facilities will include the large deployable reflector (LDR), coherent radio array, large space telescope, and coherent optical array.

The LDR is designed to operate in the infrared domain. Infrared is the most challenging part of the electromagnetic spectrum for astronomers to exploit. One reason has been the unavailability of appropriate focal plane detectors; a second is the radiation associated with normal, room-temperature bodies. The first problem is now largely solved; the only solution to the second is to cool the environment of the telescope to very low temperatures (as was done on the infrared astronomy satellite (IRAS) and is planned for the SIRTF).

At the longer infrared wavelengths, the background problem is relieved to some degree; however, very large apertures are needed for adequate angular resolution. The LDR, a mirror 20 meters in diameter, is designed to work in this domain. The LDR will function from 30 microns to a few hundred microns. At 30 microns, it will achieve diffraction-limited performance of less than 1 arc-second. It will also function as a "light bucket" at a few microns. The primary mirror will consist of individual segments, which may be made of a composite material rather than glass. The telescope will be cooled passively; the focal plane instruments must be at liquid helium temperatures. The possibility of excess infrared background in the vicinity of the Space Station and the need for passive cooling make the use of a platform necessary for this facility.

In the radio domain, it is possible to collect focused radiation from a number of independent telescopes and to combine it later at a remote point. This principle is the basis for some of the most powerful ground-based radio facilities (e.g., the very large array (VLA) in Socorro, NM). The coherent radio array platform facility, providing detection in the millimeter through submillimeter region, would be a remarkable advance in one of the last undeveloped regions of the electromagnetic spectrum. Emissions from cool interstellar clouds, molecular clouds, and star-forming regions could be observed. Such a facility would also be used in other areas of radio science -- deep space communications, radar and passive imaging of the Earth's surface, and atmospheric science.

One configuration suggested for the coherent radio array would consist of 37 antennas, each 5 meters in diameter, arranged in a T geometry with a maximum dimension of 200 meters. The facility could be constructed at the Space Station and deployed as a platform. A preliminary version with a smaller number of antennas could be constructed using the Space Station itself as the truss structure.

Although the life of the HST (to be launched in 1988) will be long, it will not be indefinite. Thus, it is appropriate to consider follow-on missions, such as the large space telescope platform facility. The simplest approach to developing this facility would be to scale up the HST. Continued improvements in optical technology, such as active segmented mirrors, and the probable availability of boosters with diameters well in excess of 4 meters make this an attractive option. The telescope could be designed with an 8-to-10-meter primary mirror, which would give it three times HST's angular resolution and ten times HST's collecting area. It would be a classical payload, fully assembled on the ground and launched directly into its operating orbit. Launching the large space telescope may require a heavy-lift capability with a large-diameter shroud, which is not currently available. A geosynchronous orbit (GEO) might be appropriate for this mission; Earth occultation and observing efficiency would be improved by a factor of two over a similar payload in low Earth orbit (LEO).

The coherent optical array is a platform facility designed to improve angular resolution and collecting area. Through this technology, it is possible to abandon single mirrors for arrays of mirrors, widely separated, to bring the light together coherently at a common focus. Since angular resolution with such an array will approach the milli-arc-second domain, the technical challenge is enormous. A number of candidate configurations have been proposed. There is no consensus on a best approach, but it is agreed that such a facility should be assembled at the Space Station.

REQUIRED TECHNOLOGY

Large observatories (the HST, GRO, AXAF, and SIRTF) will be accommodated at the IOC station, but major new initiatives will require significant configuration and technology evolution. In the team's discussions, two major requirements emerged: (1) the size and associated requirements for on-orbit assembly and (2) the data rate, which for the solar observatory and the coherent radio array could be as large as 10^9 bits. (The data rate is in fact a technical issue, as much of this load could be reduced by on-orbit data processing and storage.)

To identify missions with potential technology requirements, the team used the following guidelines:

- Missions selected would be representative, but no prioritization should be implied.
- Major attached and free-flying missions would be included.
- Technologies would not be prioritized at this level.
- Key technologies planned at IOC would be included for "visibility."
- Time frames would be identified as IOC, near (5 to 10 years after IOC), and far (more than 5 to 10 years after IOC).

The team identified both mission and system technologies because many technologies apply to both and the distinction is often unclear for attached payloads. The team also attempted to identify mission-unique "tall poles." (Technology requirements and tall pole assessments are shown in Exhibits 7-4 and 7-5 in Section 7 of this report.)

The team's principal findings on technologies needed for astronomy and astrophysics missions are summarized below:

- Astrophyics missions will include both attached and free-flying payloads.

  - Location will affect required technologies.
  - Station evolution will be essential in either case.
  - Future missions will require on-orbit assembly.

- Technologies to reduce the cost of instrument development, fabrication, and delivery will be crucial to carrying out the astrophysics missions.

- Linear scaling of cost with size will not be acceptable.
- Benefits will be derived from modular design for replication, design for container launch systems, and on-orbit assembly.

- Automation and robotics will provide major benefits for both attached and free-flying payloads. Technologies will include robots for assembly and servicing, expert systems for instrument/system operations, and telescience (for some disciplines).

- Contamination will be a major concern. Issues include avoidance/control to reduce downtime, monitoring, and cleaning of optical surfaces.

- The ability to retrieve and service a large observatory or a major component of a facility will be essential. A large pressurized workspace will eventually be required. Such a facility would:

    - Increase crew efficiency in assembly and repair of large facilities (work-hours per day)
    - Enable processes/operations not possible in an open facility
    - Improve crew performance (manual dexterity in a shirt-sleeve environment).

- Cryogenic resupply (particularly LHe) will be needed early in the evolution of the Space Station.

RECOMMENDATIONS

The team recommends that the Space Station allow more flexibility for small, rapid-turnaround experiments. These experiments have always had a special place in the NASA programs. They are entry points for new ideas, new professionals, and young people. The productivity of these experiments has frequently been extraordinary compared to their cost, and this will not change in the future.

Two essential attributes for flexibility -- mounting area and operating time -- are overabundant on the station. These assets should be combined with other Space Station attributes to allow new instruments to be developed with modest funds and to have them flown within months of their delivery. Space scientists should not have to wait for a small payload to be flown, as has been the case for attached payloads on the Shuttle.

To carry out this recommendation, it will not be enough simply to adopt concepts that have been successful in the past. The Space Station has different requirements. The Spartan, for example, was a success on the Shuttle, but only because the Shuttle could rendezvous with it. On the Space Station, the Spartan will need to have an orbital maneuvering capability of its own, which will substantially complicate the mission.

The capability for attached payloads may reduce the need for small free-flyers to instruments that simply cannot function on or near the Space Station. Thus, special care should be taken to ensure access to the station for modest attached payloads with a rapid-turnaround capability. To accomplish this, the team recommends the following measures:

- Each experimenter should be responsible for providing a totally self-contained instrument, with capability for orientation and control.

- Interface should be rigorously standardized by means of a uniform, simple mounting plate, single power, and data busses.

- A standard container should be developed into which the instrument can be built. The container should be designed for efficient packaging into the Shuttle.

- A standard protocol should be developed for unpacking the container and mounting the instrument on the Space Station.

A dedicated group at a NASA center, such as Goddard Space Flight Center's Heavy Payload Section, could play a key role in the success of such a program, just as it has in the past for sounding rockets and Spartans.

The team recommends greater use of modularity as a means of reducing cost. The key requirement for implementation of large facilities will be a substantial reduction in cost and unit complexity. A cost of $1.0 billion for large space astronomical facilities is the maximum that can be justified, and only one such facility can be started every 5 years. (Even at $100 million, only one can be started per year.) Each of the facilities suggested here, if costed according to current models, will be priced at much more than $1.0 billion. New approaches will be needed if they are to be implemented.

In the development of new astronomy facilities, the facilities should be divided into nearly identical modules that can be replicated inexpensively and containerized for efficient transport into orbit. To implement this recommendation, the team suggests that NASA identify a number of strawman facilities for a detailed engineering study. This would allow the development of realistic requirements and cost. For this purpose, NASA may wish to issue a "Dear Colleague" letter and undergo a selection process. The resulting studies are likely to yield a number of common technical concepts, including:

- Highly automated techniques for assembling trusses and mounting modules at the Space Station
- Efficient containerization for transporting modules and truss material to the Space Station
- New cost guidelines based on the manufacture of large numbers of identical modules that make up a facility
- New techniques and technologies to process and store large quantities of data at the Space Station and to transmit large data rates to the ground
- Guidelines and techniques for minimization and standardization of interfaces.

To implement these modular-based facilities, the team recommends that NASA support, where possible, an evolutionary approach to their development. For example, a preliminary version of the coherent radio array could be built with a small number of radio telescopes (perhaps five) attached to the Space Station itself. Similarly, the XLA might be initiated with ten modules, each measuring 1 square meter.

Even though launch costs are not currently budgeted against NASA's astronomy missions, the availability of launch vehicles is likely to be critical to the feasibility of these facilities. The team recommends that NASA adopt the guideline in the National Space Transportation and Support Study that launch costs be brought down by one order of magnitude.

The team recommends branching as a solution to several problems. Although a number of the facilities described in this report are attached to the Space Station, there may be important reasons to convert all facilities to platforms at LEO and to transfer some to higher orbits. One overall consideration for moving off the Space Station is crowding: although there do not seem to be natural limits to the size of the Space Station, it may be desirable, for operational reasons, to off-load portions of the Space Station. The main reasons for moving astrophysics platforms to high orbits are the absence of Earth occultation (the move may double the observing efficiency) and ease of data return and operations. Considerations for specific facilities are as follows:

- XLA. Earth occultation introduces significant aliasing at orbital periods and other discontinuities in studies of time variability of source radiation. Operation at GEO or a higher orbit would eliminate this problem, but at a penalty of increased background radiation.

- Coherent Radio Array. Operation at GEO would eliminate the problem of Earth occultation of sources, relieve the data retrieval problem, and reduce the terrestrial background.

- Solar Observatory. Contamination at the Space Station may be a serious problem for many solar instruments. This problem could be solved by converting the facility to a platform. Operation at GEO would allow continuous solar monitoring, which is important for tracking transient phenomena and studying solar oscillations.

NASA should be prepared to convert attached facilities to platforms. The conversion should be possible as a modification or extension rather than replacement of an existing facility. NASA should also be prepared to consider transporting and supporting some facilities in a high orbit.

Finally, the team recommends that the Space Station include a large pressurized hanger for work on large facilities. The only shirt-sleeve working environment readily available at the Space Station is in the modules. The largest access to this space is a door 1.3 meters in diameter, which allows for the entry of items with a greatest dimension of about 1.5 meters. Thus, only instruments and subassemblies can be brought into a pressurized space where they can be worked on by the crew. Success in developing, maintaining, and upgrading externally mounted facilities will depend on the ability of robots and the availability of astronauts for extravehicular activity.

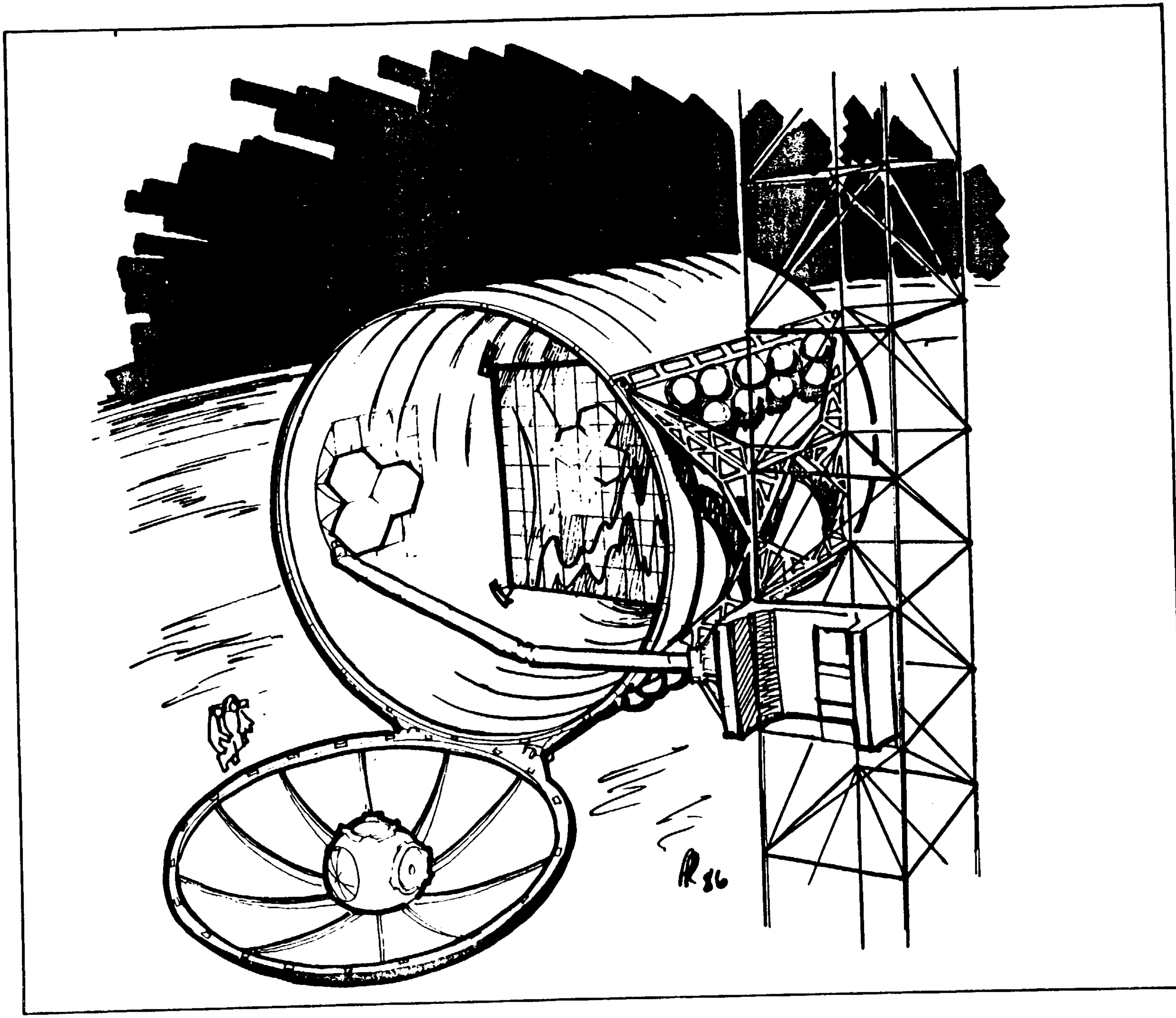
The large pressurized hanger will provide support for facility repair, refurbishment, and reconfiguration. The hanger should be about 30 meters in diameter and 60 meters long. The entrance port, 30 meters in diameter, should be capable of being fully pressurized so that the crew can work on large facilities. Exhibit 1-5 shows a large observatory element being brought into such a hanger for servicing.

NASA should ensure that the Space Station can accommodate a large hanger. The agency should also initiate engineering studies to determine the cost of the hanger and its impact on the station. The pressurized hanger would provide auxillary benefits. It would represent a new kind of technical development that could be of special importance to NASA in meeting the goals of the National Commission on Space for advanced spaceports and a lunar base.

ISSUES

The team identified one issue of particular concern to astrophysics missions: contamination. Probably the most serious constraint on conducting long-term astronomical studies on the manned base of the Space Station is the cloud of dust and gas that will inevitably envelop the station and settle on any exposed surface. Indeed, the infrared astronomy community has essentially abandoned the station as an operating site. Another contamination problem is the continuing accumulation of

EXHIBIT 1-5
PRESSURIZED HANGAR



debris in LEO. There is increasing evidence from impacts on the Shuttle that the amount of material is building up. The potential for surface erosion and more serious damage from these man-induced micrometeorites is a significant hazard to the Space Station. Debris has also become a matter of concern at the international level.

The team recommends that NASA take the lead in ensuring a clean environment at the Space Station. NASA should also address the debris issue to ensure that the buildup of material in space does not continue.

2. COMMUNICATIONS TEAM REPORT

2. COMMUNICATIONS TEAM REPORT

The communications satellite industry offers a concrete example of the commercial use of space. Once entrepreneural, it has evolved into a highly mature industry that is both competitive and conservative. Its most important characteristic is that it is economically driven; that is, it seeks the lowest cost consistent with acceptably low risk.

The deliberations of the communications team were assisted by information provided by Ford Aerospace under an ongoing contract with the NASA Lewis Research Center.* This information included background technical and economic analyses on the potential uses of the Space Station to support communications satellites.

In its discussions, the team assumed that the Shuttle would be available for commercial launches to low Earth orbit (LEO) and/or the Space Station. Without the Shuttle, the potential benefits described in this report would be seriously compromised and would need to be reevaluated.

The team used a three-step process to define requirements of the communications satellite industry. It first identified several activities, procedures, and operations (APOs) that have potential economic benefits or that would enable new missions. It then established time scales for introducing these capabilities into the Space Station infrastructure. As a last step, the team defined the required Space Station technologies, configurations, and facilities.

---

* Ford Aerospace and Communications Corp. Communications Satellite Systems Operations with the Space Station. Volume I, Executive Summary, NASA CR 179526; Volume II, Technical Report, NASA CR 179527. February 1987.

IDENTIFICATION OF EVOLUTION ACTIVITIES, PROCEDURES, AND OPERATIONS

Cost-saving APOs, summarized on Exhibit 2-1, were identified as follows:

- Space-Based Orbital Transfer Vehicle (OTV) Delivery to Geosynchronous Orbit (GEO) (2000-2005). Budgetary constraints may preclude development of a space-based OTV concurrently with the Space Station. The OTV could reasonably be available by 1998, although an additional 2 years may be required for a "flight proven" vehicle. This time frame is also compatible with the launching of NASA-developed GEO platforms (communications or Earth observation/ science) in the 10- to 20-thousand-pound category.

- LEO Retrieval, Storage, and Repair (1995-2000). This capability could exist a relatively short time after Space Station initial operating capability (IOC) -- as early as 1995. The functions could be performed in the near vicinity of the Space Station via extravehicular activity (EVA) or orbital maneuvering vehicle (OMV).

- Deployment and Checkout (Go - No Go) (1995-2005). This capability may also exist shortly after Space Station IOC. Deployment of satellite appendages may be performed by EVA or teleoperator/robot.

- GEO Servicing/Upgrade (2000-2010). GEO servicing will require a space-based OTV plus an OMV with appropriate front-end kits. Therefore, the availability of this capability must coincide with that of the OTV (year 2000). However, due to the complicated nature of GEO servicing, this capability may take a longer time to evolve.

EXHIBIT 2-1
APOs TO SAVE COSTS:
ASSUMPTIONS, REQUIREMENTS, AND BENEFITS

1.1 Space-Based OTV Delivery to GEO

- Expected initial application--2000 to 2005
- Assumes planned NASA OTV user charges
- Assumes mid-level cryogenic propellant costs
- Applicable to relatively high numbers of launches--10 to 20 communication satellites per year
- Assumes consistent transport scheduling
- No adoption by industry until flight proven
- Requires efficient low-cost OTV-to-spacecraft mating techniques
- Provides reduced risk and lower insurance fees

1.2 LEO Retrieval, Storage, and Repair

- Expected initial application--1995 to 2000
- For failed spacecraft or launch systems in LEO, retrievable by OMV
- Relatively insensitive to OMV user charge
- Requires storage facility at station
- Requires flexible OMV scheduling and rapid availability for emergencies
- Assures mission success

1.3 Deployment and Checkout (Go - No Go)

- Expected initial application--1995 to 2005
- Requires low-g OTV transfer, which could be spacecraft propulsion or OTV
- Requires repair capability at the Space Station
- Provides reduced risk and lower insurance fees

1.4 GEO Servicing and Upgrade

- Expected initial application--2000 to 2010
- Requires OMV/OTV telerobotics
- Requires spacecraft designed with ORUs (modules)
- Requires dependable servicing schedule
- Economics require servicing of multiple spacecraft for each mission
- Potential large pay-off for extended life and new technology insertion

APOs to enable new missions, summarized on Exhibit 2-2, were identified as follows:

- Research and Development (R&D) of Large Deployable Antennas (1995-2000). This activity can begin fairly soon after Space Station IOC if the enabling requirements are met (see Exhibit 2-4).

- R&D of LEO Assembly, Deployment, and Checkout for Large, Complex Systems (1995-2000). This activity will require a servicing bay, a mobile remote manipulator system (MRMS), and strong-back earlier than currently planned for large antennas and GEO platforms.

- Operational Application to LEO Assembly, Deployment, Checkout, and Boost to GEO (2000-2005). The operational application of large deployable antennas and large complex systems will begin after R&D activities in the 1995-to-2000 period are completed. A flight-proven OTV may not be available until 2000.

REQUIRED TECHNOLOGY

Based on the APOs defined in the preceding discussion, the team tabulated the Space Station resource requirements, as shown in Exhibit 2-3. The list of requirement categories was taken from the first Space Station Evolution Workshop report. The importance of each requirement is indicated as high (H), medium (M), low (L), or not used (X). The most significant requirements are explained further in Exhibit 2-4. A condensed summary is given in Exhibit 2-5.

EXHIBIT 2-2
APOs TO ENABLE NEW MISSIONS: ASSUMPTIONS AND REQUIREMENTS

2.1 R&D of Large Deployable Antennas

- Expected availability--1995 to 2000
- Driven by inability to test adequately on the ground
- May be tested as a co-orbiting free flyer
- Applicable to reflector systems
- Assumes automated deployment
- Requires Space Station-based test facility
- May require station structure for deployment and testing
- Requires space-based antenna range

2.2 R&D of LEO Assembly, Deployment, and Checkout for Large, Complex Systems

- Expected availability--1995 to 2000
- For development of teleoperator/robotic assembly and/or deployment and checkout techniques
- Requires service/storage bay
- Materials handling must be considered (debris, modules, etc.)
- Requires development of disciplines for handling large structures in vicinity of the Space Station
- Requires developing techniques for mating of large structure to OTV

2.3 Operational Application to LEO Assembly/Deployment/Checkout/Boost to GEO

- Expected availability--2000 to 2005
- Construction, test, assembly, deployment, and checkout techniques developed in 2.1 and 2.2 expanded to operational status, including mating with the OTV
- Requires availability of service and storage bay
- Relies on automation and robotic applications to minimize EVA

EXHIBIT 2-3
SPACE STATION RESOURCE REQUIREMENTS FOR COMMUNICATIONS SATELLITES

X = Not Used M = Medium
H = High Use L = Low

	APOs						
REQUIREMENTS	1.1	1.2	1.3	1.4	2.1	2.2	2.3[1]
Attitude Control System	X	X	X	X	L	L	L
Automation and Robotics	M	H	H	H	H	H	H
Communications and Telemetry	L	L	L	X[2]	H[3]	H[3]	H[3]
Data Management System	L	L	L	X	L	L	L
Extravehicular Activity	L	H	H	X	L	H	L
Environmental Control/Life Support System	X	X	X	X	X	X	X
Fluids	X	X	X	L	X	X	M
Manned Work Stations	L	M	M	X	M	M	H
Power	L	L	L	L	L	L	L
Structures	X	M	L	X	L	H	H
Propulsion	X	X	X	X	X	X	X
Mechanisms	L	L	L	X	L	H	H
Thermal	L	M	L	X	X	M	M
Materials	X	X	X	X	X	L	L
OTV	H	X	H/X[5]	H	X	X	H
OMV	X	H	X	H[4]	H[4]	H[4]	H[4]

1 These numbers are keyed to the APO descriptions in Exhibits 2-1 and 2-2

2 Space Station bypassed - C&T is direct between earth and GEO

3 Tracking

4 Smart front-end requirement for OMV

5 Low thrust by OTV (2000 - 2005) is H, by spacecraft (1995 - 2000) is X

EXHIBIT 2-4
TECHNOLOGY REQUIREMENTS FOR APOs

COST SAVING APO	REQUIREMENTS/ISSUES	TECHNOLOGY
1.1 Space-Based OTV Benefit- Decreased launch cost. Insurance cost relief in question.	OTV availability and cost	LEO-to-GEO transfer MINIMUM of 5,000 lbs Low-cost transport to LEO
1.2 LEO Retrieval/ Storage/Repair Benefit-Relaunch avoidance. Minimize delay in earning revenue. Lower insurance rates.	OMV availability and cost Service and storage bay EVA use for unscheduled repair A&R to minimize EVA	OMV retrieval of failed spacecraft Teleoperator/ robotic activity
1.3 Deployment and checkout (go - no go) Benefit- Reliability enhancement, lower insurance rates.	Low thrust OTV cost Deployment of appendages and performance of go - no go checkout EVA versus A&R for deployment	Low thrust OTV Teleoperator/ robotic activity
1.4 GEO Servicing and Upgrade Benefit- Revenue enhancement	OMV and OTV avail- ability and cost OMV with smart front end	LEO to GEO transfer and return of OMV and service modules Economics requires servicing multiple satellites in one mission OTV lift capabil- ity, 20,000 lb to GEO

EXHIBIT 2-4
(CONTINUED)

NEW SYSTEM ENABLING APO	REQUIREMENTS/ISSUES	TECHNOLOGY
2.1 Large Deployable Antenna R&D	OMV with smart front end Tracking of separate structure On-orbit test equipment Proximity of LDA to Space Station	LDA system realization On-orbit testing of LDA LDA deployment
2.2 LEO Assembly/ Deployment and Checkout R&D	OMV with smart front end Assembly of large structures at Space Station Tracking and testing	Advanced satellite communication architecture Teleoperator/ robotic activity
2.3 Operational Application of 2.1 and 2.2	All of 2.1 and 2.2 OMV/OTV availability and cost Minimum EVA Extensive use of A&R	All of 2.1 and 2.2 Low-thrust OTV

EXHIBIT 2-5
SUMMARY OF COMMUNICATIONS SATELLITE REQUIREMENTS ON THE SPACE STATION

- Space-based OTV, low cost, low thrust (0.1g)
- Space-based OMV, low cost
- Teleoperator/robotic capability
- EVA (minimized by automation and robotics capabilities)
- Assembly/deployment/checkout of large structures
- A&R/EVA LEO servicing/checkout/repair (scheduled and unscheduled
- A&R GEO servicing/upgrade (scheduled)
- Space Station servicing/storage bay
- Space Station test facilities for large antennas and advanced spacecraft

The following exhibits show some possible concepts for use of the Space Station by the communications satellite industry. Exhibit 2-6 is an artist's conception of the deployment of a large aperture antenna for test and evaluation using the Space Station. Exhibit 2-7 shows a concept for OMV delivery to GEO using an OTV. Exhibit 2-8 shows a concept for a GEO servicing system, and Exhibit 2-9 shows a concept for an OTV carrying two satellites on a multiple payload carrier.

ISSUES

The team felt that two areas in particular should be given further study; the economics of launches to the Space Station by expendable launch vehicles (ELVs) and the benefits of ground-based vs. space-based OTVs.

APOs with potential cost benefits were identified on the premise that the Space Station would be used as a staging base and that launch to the station would be accomplished by the Shuttle. However, recent policy changes would shift commercial satellites to ELVs, resulting in less frequent use of the Space Station as a staging base.

Although it is possible to launch communications satellites to the Space Station on ELVs, only those launched from the Eastern Test Range (ETR) are likely to stage at the Space Station. However, ELVs launched from near-equator sites (such as Ariane vehicles) have a performance advantage over ETR-launched ELVs. In addition, subsidized ELVs may capture a significant share of future communications satellite launches.

Launching from sites other than the ETR will require a plane change to the 28-degree Space Station orbit. Such a change will result in some loss of performance and additional cost. These penalties will probably offset, if not exceed, the economic

EXHIBIT 2-6
LARGE APERTURE ANTENNA TEST

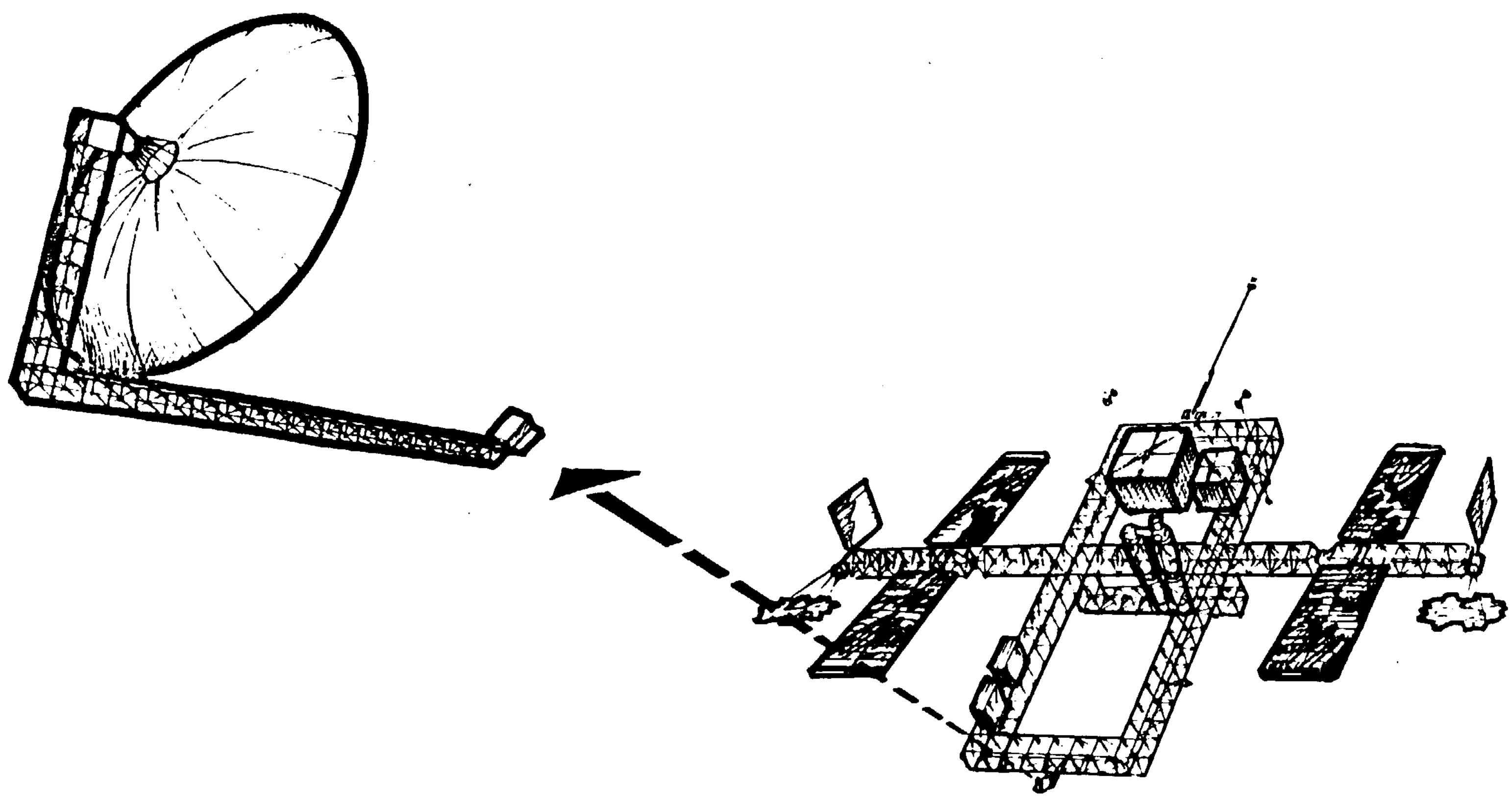


EXHIBIT 2-7
OMV DELIVERY TO GEO BY OTV

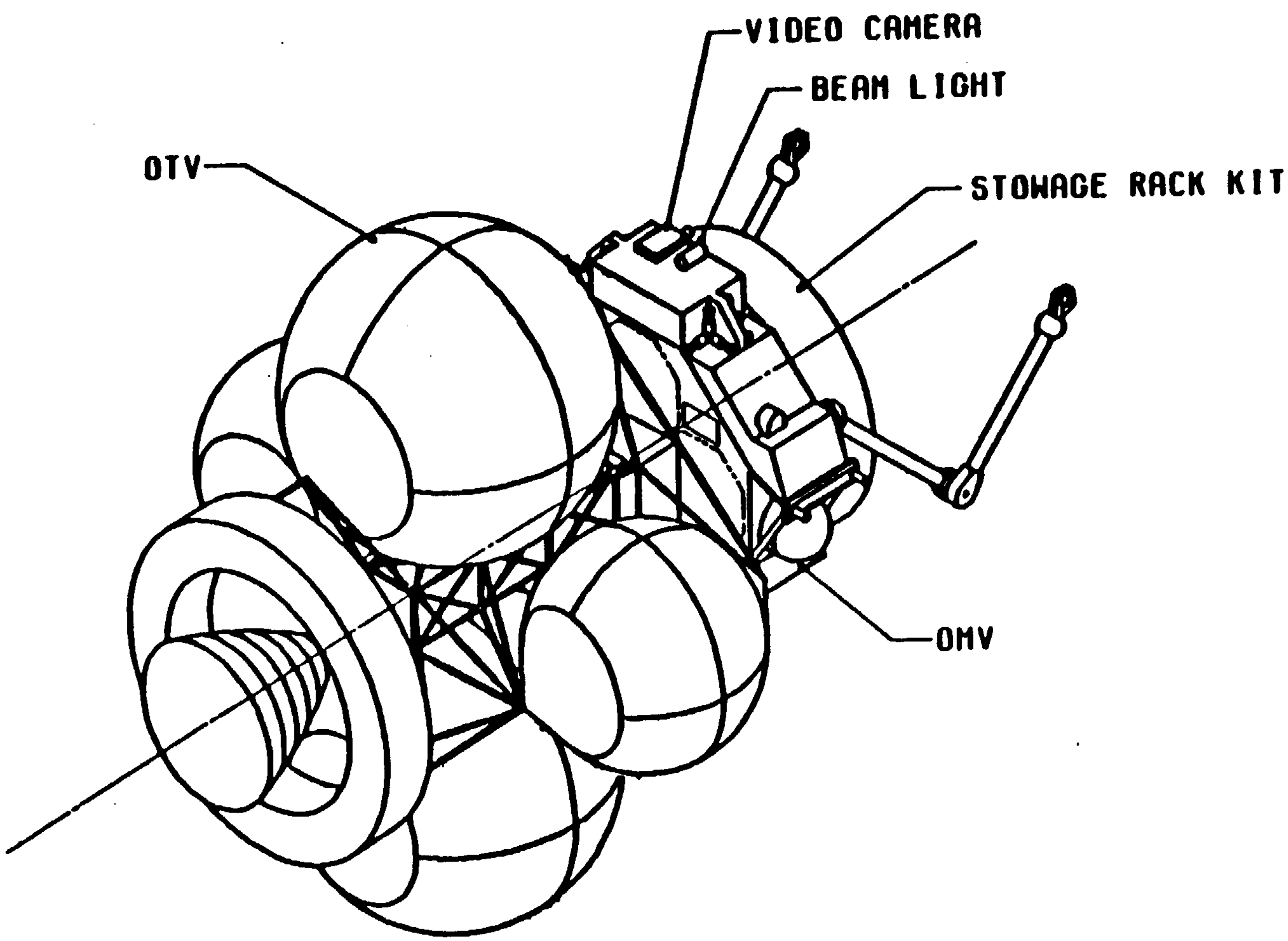


EXHIBIT 2-8
GEO SERVICING SYSTEM CONCEPT

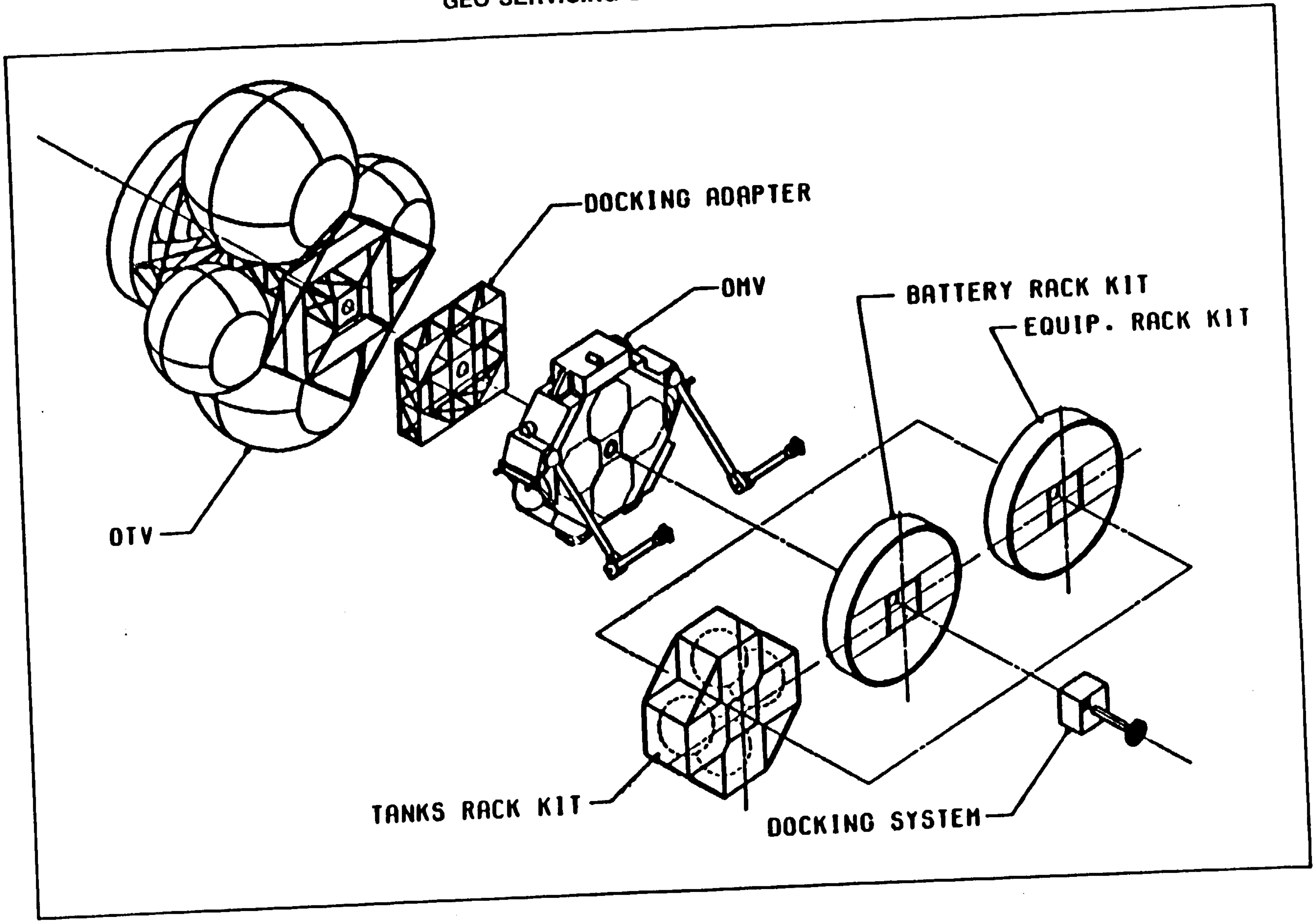
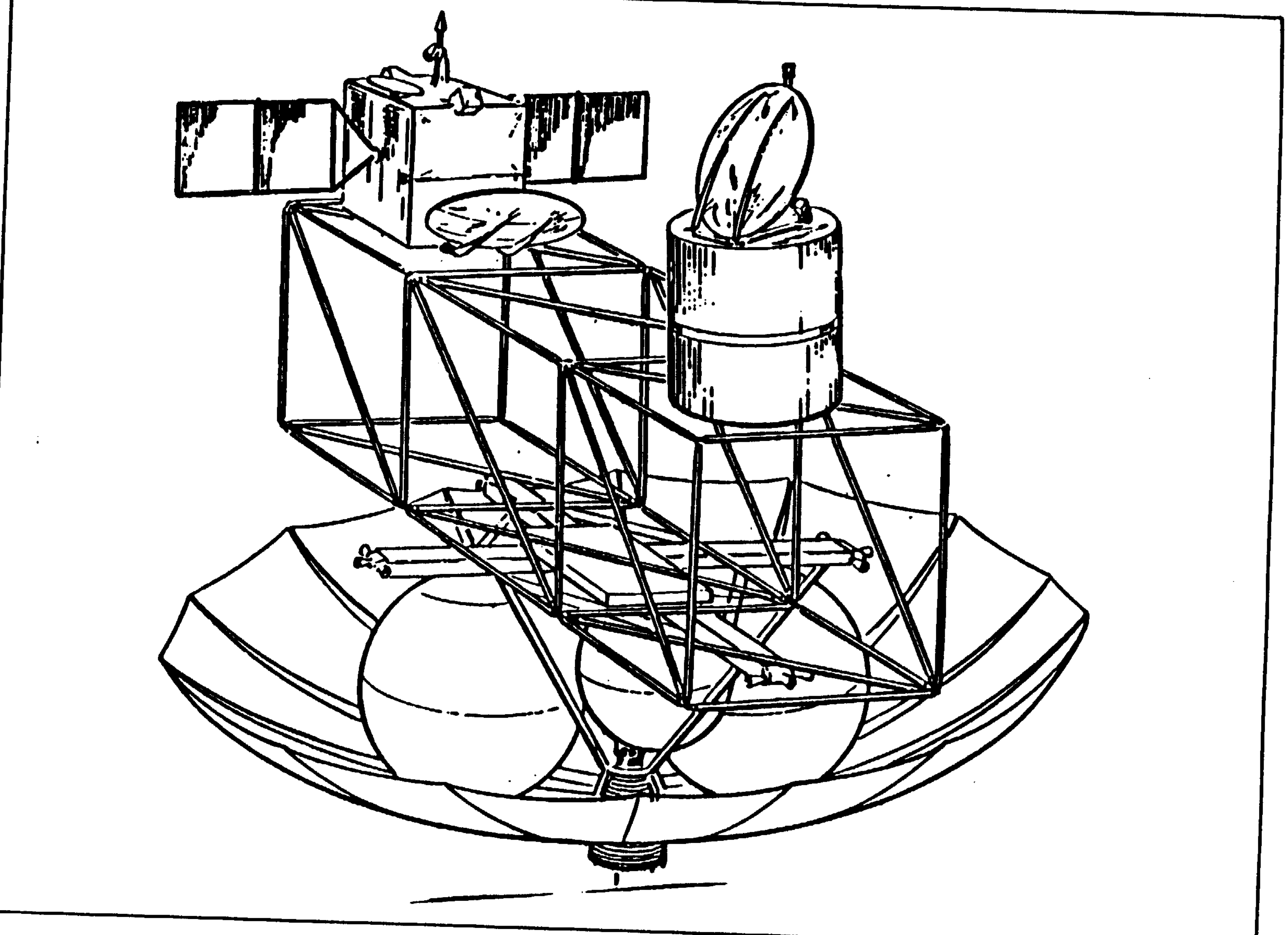


EXHIBIT 2-9
OTV WITH MULTIPLE PAYLOAD CARRIER



advantages of the APOs identified as cost saving. The economics of the APOs when the satellites are launched on ELVs should be rigorously reevaluated.

A related issue is the question of whether satellites launched by ELVs can be returned to Earth for repair on the Shuttle. However, because the number of communications satellites requiring return to Earth will likely be small, this is not expected to be a significant problem.

The benefit of ground-based vs. space-based OTVs is a subject still under discussion. A preliminary analysis conducted by Ford Aerospace indicates that a space-based OTV would be more beneficial than a ground-based OTV for the APOs investigated. Other studies indicate that neither would provide an advantage over the other. This is an area that will require continuing study.

One factor, in particular, should be considered. When communications satellites with deployed appendages or antennas are launched from LEO to GEO, a low thrust on the order of 0.1 g is required. Under these conditions, the OTV round-trip mission time (LEO-GEO-LEO) will be greater than the Shuttle's orbit stay-time capability. As a result, a ground-based OTV will have to be maintained in LEO or at the Space Station while awaiting its return to Earth on a subsequent Shuttle. The resources required for this maintenance should be considered in any system cost tradeoff study.

RECOMMENDATIONS

The team's observations and recommendations fell into three areas: technical, economic, and policy.

In the technical area, the team felt that telerobotics for all APOs (except routine launch on an OTV) will be a key technical driver and, in some cases, may be an enabling capability. Telerobotics will be less costly and much safer than EVA.

NASA support of enabling R&D on large antennas and spacecraft structures (and subsequent operational systems) is essential to maintaining the U.S. lead in communications satellite technology and to providing the U.S. industry with technology options for the future. The Space Station offers unique capability in this regard.

In the economic area, the team felt based on preliminary analysis that several APOs will have the potential for payoff. However, the prices likely to be charged for OMV, OTV, and Space Station services are uncertain.

The economic feasibility of using the Space Station to stage commercial communications satellites needs to be carefully assessed on a continuing basis. Immediate attention should be given to the impact of launching on ELVs.

To be economical, the OTV, as currently envisioned, must carry multiple "conventional" spacecraft. Scheduling and spacecraft compatibility may be problem areas.

The communications satellite industry is not currently motivated to "push" for Space Station capabilities to meet its needs. As a result, the economic payoff is generally perceived to be small.

The team also felt that certain policies must be established if communications satellite companies are to use the Space Station fully. NASA must develop policies to ensure regular, reliable, and certain access. It must provide a means for companies to make a realistic assessment of the payoff for using the Space Station. To do this, NASA must continue to work toward building a credible data base of Space Station technical features, capabilities, and costs. It must also establish a firm pricing policy and commit to appropriate long-term work to maintain business conditions so that companies can confidently predict their risk and cost.

3. EARTH OBSERVATIONS TEAM REPORT

3. EARTH OBSERVATIONS TEAM REPORT

Traditionally, we have studied our planet in parts, concentrating on the atmosphere, oceans, land surfaces, rock layers, ice, and biota as individual systems. We have paid less attention to how these parts interact. However, in the past decade, an increasing number of scientists have been looking at how the physical, chemical, and biological parts of the Earth interact. They hope to understand such phenomena as changes in the ozone layer, increases in atmospheric carbon dioxide, acid precipitation, and "El Nino" related changes in weather patterns. NASA's Earth observing system, named EOS after the Greek goddess of dawn, is a multidisciplinary mission planned for the 1990s. It will provide observational capabilities as well as a data and information system needed to understand the Earth as a total system.

MISSION REQUIREMENTS

The deployment scenarios for Earth observation instruments incorporate requirements for measurement simultaneity, payload synergy, fields of view, and other observational factors. The strategy calls for instruments to be placed on polar platforms developed as part of the Space Station complex. As planned, three platforms will be launched during Space Station initial operating capability (IOC, 1993 to 1995). Two of the platforms will be provided by the United States and one by the European Space Agency.

The two afternoon platforms will fly at altitudes of 824 kilometers and 540 kilometers, with equator crossing times between 1:00 p.m. and 1:30 p.m. The morning platform will fly at 824 kilometers, and its crossing time will be between 9:30 a.m. and 10:30 a.m. Additional instruments will be added to these platforms at 2-year intervals after IOC. Current plans call for Shuttle-based servicing of the platforms and instruments. This servicing capability will make possible the planned EOS mission life of 15 years, the time interval required for study of some long-term processes.

The instruments to be deployed are classified as NASA-provided research instruments, current operational instruments, and research instruments that may become operational in the near future. Some instruments of research interest to NASA's EOS are considered operational instruments. It is assumed that NOAA will develop, fly, and produce data from those instruments within the EOS payload. Thus, the aggregate payload of NASA- and NOAA-provided instruments is expected to fulfill the requirements for EOS.

Other Earth observation instruments will be payloads attached to the Space Station and serviced by means of its infrastructure. A lidar atmospheric wind sounder (LAWS) and a high-resolution, multichannel microwave radiometer (HMMR) on the manned core would provide virtually complete coverage of the important tropical latitudes. A tropical rainfall instrument would provide important synergism with a lidar wind instrument for a wide range of interdisciplinary investigations.

Other instruments may be deployed as part of a solar terrestrial observatory (STO). The STO is a problem-oriented instrument payload that will permit investigations of the solar atmosphere, the interplanetary medium, and the Earth's magnetosphere, ionosphere, and atmosphere. The initial STO will involve use of a number of large instruments originally designed for Shuttle/Spacelab missions. These instruments will be placed on the Space Station elements to take advantage of the station's long duration in orbit, high power availability, in-orbit servicing, and multidirectional pointing.

The STO will consist of instrument groupings on the Space Station top and lower keels and on the polar platforms. Because these instruments for the initial STO are (with few exceptions) currently under development for flight on Shuttle missions, it is expected that the STO will be a cost-effective, realizable payload for the initial Space Station. Studies are currently under way to determine how these instruments should be modified and upgraded for use on the Space Station. The initial selection and placement of the STO instruments will enable scientists to begin a program of interactive cause-and-effect experiments to acquire a better understanding of the Earth-space system.

Earth observation systems must also include advanced space platforms in geosynchronous orbit (GEO). Since 1974, GEO satellites have carried imager/sounder instruments providing high-resolution visible and infrared images of the Earth. The infrared channels of the sounding instruments have provided temperature and moisture profiles over large areas of the Earth. NOAA currently operates two GEO satellites and should continue to maintain and improve them. GEO platforms with increased weight and power capabilities will permit advanced imager/sounder instruments operating in the visible, infrared, and microwave spectral regions. The added capability of microwave sounding is not currently available because of the large antenna required for spatial resolution at these high altitudes. Such capability is being studied as a possible addition to the next generation of NOAA GEO satellites in the mid 1990s. These platforms may be expected to extend many of the capabilities and benefits of the Space Station polar platforms to GEO in the late 1990s.

These platforms will offer several advantages for Earth observation. High temporal resolution -- limited only by instrument design and cost -- can be brought to bear on the study of rapidly changing, global atmospheric phenomena. In land and ocean surveys, high temporal resolution will help minimize data loss resulting from cloud cover and unfavorable atmospheric conditions. Platforms in GEO will, in addition, provide a fixed-reference geometry for a given Earth location. This will facilitate data analysis and the study of processes with diurnal variations.

TECHNOLOGY REQUIREMENTS

Various studies have made it clear that significant benefits will be realized from the use of automation and robotics on the Space Station. In addition, P.L. 98-371 states that the initial Space Station should use existing and future automation and robotics capabilities to enhance its availability, safety, and productivity. Missions identified for EOS will require these capabilities to serve attached payloads, co-orbiting platforms, polar platforms, and platforms at GEO. Automation and robotics may also be used on the GEO platform mission for on-orbit assembly and checkout of large antennae. Both of these applications could use flexible telerobotic services currently being defined by the NASA Goddard Space Flight Center.

In the past, robots have had insufficient capability to conduct the flexible servicing or assembly tasks currently envisioned for EOS missions. Even now, space robots are unable to perform highly dexterous and complex tasks. But current developments in microelectronics, increased computing power, and artificial intelligence have made the use of an intelligent robot a major element of a growth station. The current plan includes telerobotic capability for the initial station and progressive evolution toward intelligent robotics.

The transmission bandwidth of the TDRSS downlink has been identified as a critical limitation for Earth observations. The Earth observation capability encompasses all elements of the

Space Station infrastructure, including LEO and GEO platforms as well as the core station. Therefore, there will be a high demand for transmission bandwidth to ground facilities. A possible solution to the bandwidth limitation problem would be to use laser communications to increase the bandwidth for Earth observing instruments. Systems provided must be able to perform the telescience/expert systems functions that will be incorporated in the payload package.

Earth observing instruments will be capable of generating data at rates that exceed the capability of the TDRSS. The evolution of these instruments and the increase in Earth observations in general will compound the transmission problem. One solution would be to perform data processing on board the Space Station or platform. This solution, however, will be less acceptable to the science community than to the operational users. On-board processing would require parallel processing architectures and other high-performance technologies. The on-board processors must be programmable to allow algorithm alterations and fault tolerance so that crew interaction for maintenance and repair is kept to a minimum. In the absence of on-board processors for Earth observation payloads, mass storage will be required to hold the data temporarily for transmission. Optical mass memory could be used for temporary storage of large volumes of data.

Extravehicular activity (EVA) to repair and maintain instruments and equipment must be made safer, faster, less contaminating, less tiring, and more dexterous. There are a number of possible options.

The storage and transfer (loading) of hypergolic fuels (bipropellants) and cryogenic fuels (oxygen/hydrogen) in quantities sufficient for missions to GEO, lunar, or planetary sites will pose a safety hazard. The problem should be addressed early in Space Station planning.

A unique requirement for power storage has been identified for the STO. To support plasma investigations, an energy storage system will be needed that is capable of holding a large quantity of energy and releasing it in a short-duration pulse. This could require new storage technology, possibly a flywheel approach.

Improvements in active thermal control technology will enhance the Earth observation capability. Many experiments will require accurate thermal control (e.g., lasers, detectors). Lasers generate waste heat intermittently. With the orbital replacement unit (ORU) concept, the laser cooling loop (including the radiator) must be a part of the laser ORU boundary. Technology should be developed for demountable, repeatable thermal transfer at heat pipe interfaces (ORU boundary). Long-life refrigeration systems for detectors should also be developed.

Several kinds of special tools, such as the module exchange tool used on the solar maximum repair, are required for exchange of ORUs and instruments. These tools must be interchangeable -- capable of being held by the end effectors of the remote manipulator systems or by the work effectors of the robotic servicers.

ORUs and instruments on platforms and the Space Station should be made with modular subunits so that they can be repaired by exchanging these units. EVA astronauts or robots would accomplish the exchange using special tools.

All systems on platforms and the Space Station must be designed for serviceability. This includes ORU and module subunit exchange, optics cleaning, and fluid resupply.

On-orbit workstations will be required for controlling externally attached Space Station instruments and instruments on co-orbiting platforms, such as the STO. These workstations must be software-reconfigurable to allow use with different kinds of instrument payloads.

Systems must be available for automatic rendezvous and docking of servicing and supply vehicles at platforms and the Space Station. These systems could be used on ELVs and commuter vehicles.

Systems will be needed aboard the Space Station and platforms to measure gas, particulates, and deposits in the environment. Accurate measurements will enable control of venting and efflux and thus minimize interference with instruments.

All Space Station, platform, and payload systems must be designed to minimize electrical and magnetic interference at all frequencies. The proper grounding architecture must be defined and maintained.

Shuttle lift capability should be improved. The maximum weight to orbit has a direct impact on the number of flights needed to accomplish a specific goal. If limited to a single flight, research projects can achieve only a small percentage of their objectives. The Shuttle's weight-to-orbit capability could be improved through "heads up flight" (ascent flight with the Shuttle positioned above the external tank) or similar schemes. A one-time cost would provide enduring enhancement and a life-cycle cost payback.

To perform in situ servicing of platforms, a low-energy transporter, such as an orbital maneuvering vehicle (OMV) will be needed to carry ORUs, instruments, and robot servicers from the Space Station, the Shuttle, and ELVs.

Large, fragile observation spacecraft that have been assembled at the Space Station must be transferred to higher orbits. To do this, a propulsion system that accelerates the spacecraft at a maximum of 0.1 g will be required.

The servicing and repair of observation spacecraft in GEO must be done in situ, by robots. To transport the necessary ORUs and equipment in a reasonable time, a high-energy, moderate-acceleration carrier vehicle (like an orbital transfer vehicle (OTV)) will be desirable.

RECOMMENDATIONS

For Earth observation missions, it will be necessary to acquire long-term, continuous data from a multiplicity of instruments. The Space Station should include three platforms in polar sun-synchronous orbit, one platform in a polar or high-inclination orbit, a geostationary platform, and attached payloads serviced by means of the Space Station infrastructure. Periodic servicing will be needed to ensure operational reliability. This includes servicing of platforms in GEO that are not currently considered part of the Space Station program. Ease of access and modularity will be important for technological improvements.

Evolution of the Space Station for Earth observation systems could follow one or more of the following paths:

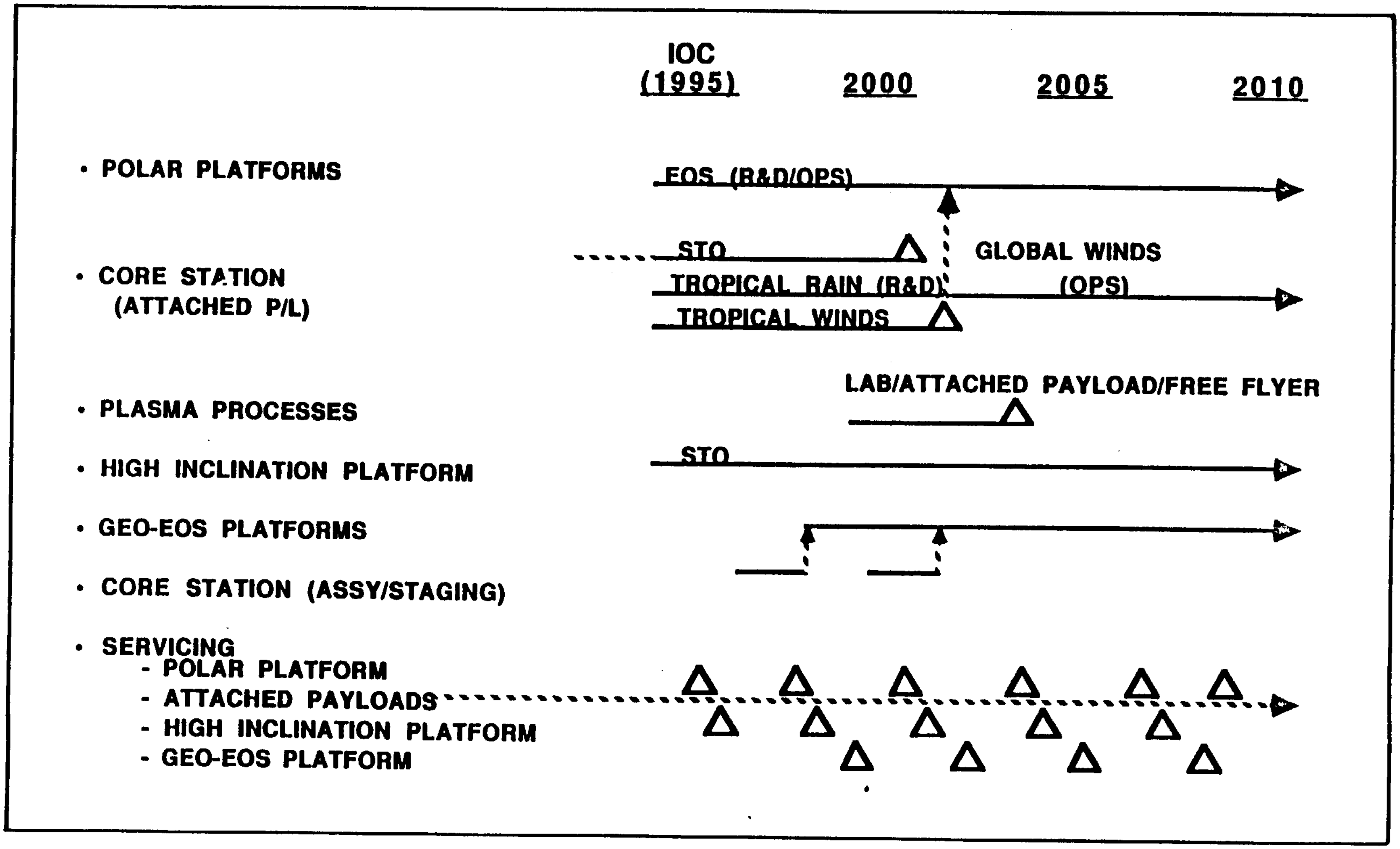
- Additional platforms may be required when requirements exceed the capability of a single unit or when orbital operational requirements dictate.

- Improvements may be incorporated or instruments added as technological upgrades into the overall measurement strategy.

- Serviceable GEO platforms may be added.

Figure 3-1 shows a schedule that integrates scientific program requirements with the overall schedule and plans for the Space Station elements.

EXHIBIT 3-1
EARTH OBSERVATION
EVOLUTIONARY PATH/MISSION MODEL



4. LUNAR AND PLANETARY MISSIONS TEAM REPORT

4. LUNAR AND PLANETARY MISSIONS TEAM REPORT

The President's National Commission on Space (NCOS) has recommended an agenda for the U.S. space program over the next 50 years. A central theme in its vision is the expansion of human activity to the Moon, to Mars, and ultimately to the rest of the solar system as "humanity's extended home." The gateway to the planets is a spaceport in low Earth orbit (LEO) associated with NASA's planned Space Station (Exhibit 4-1).

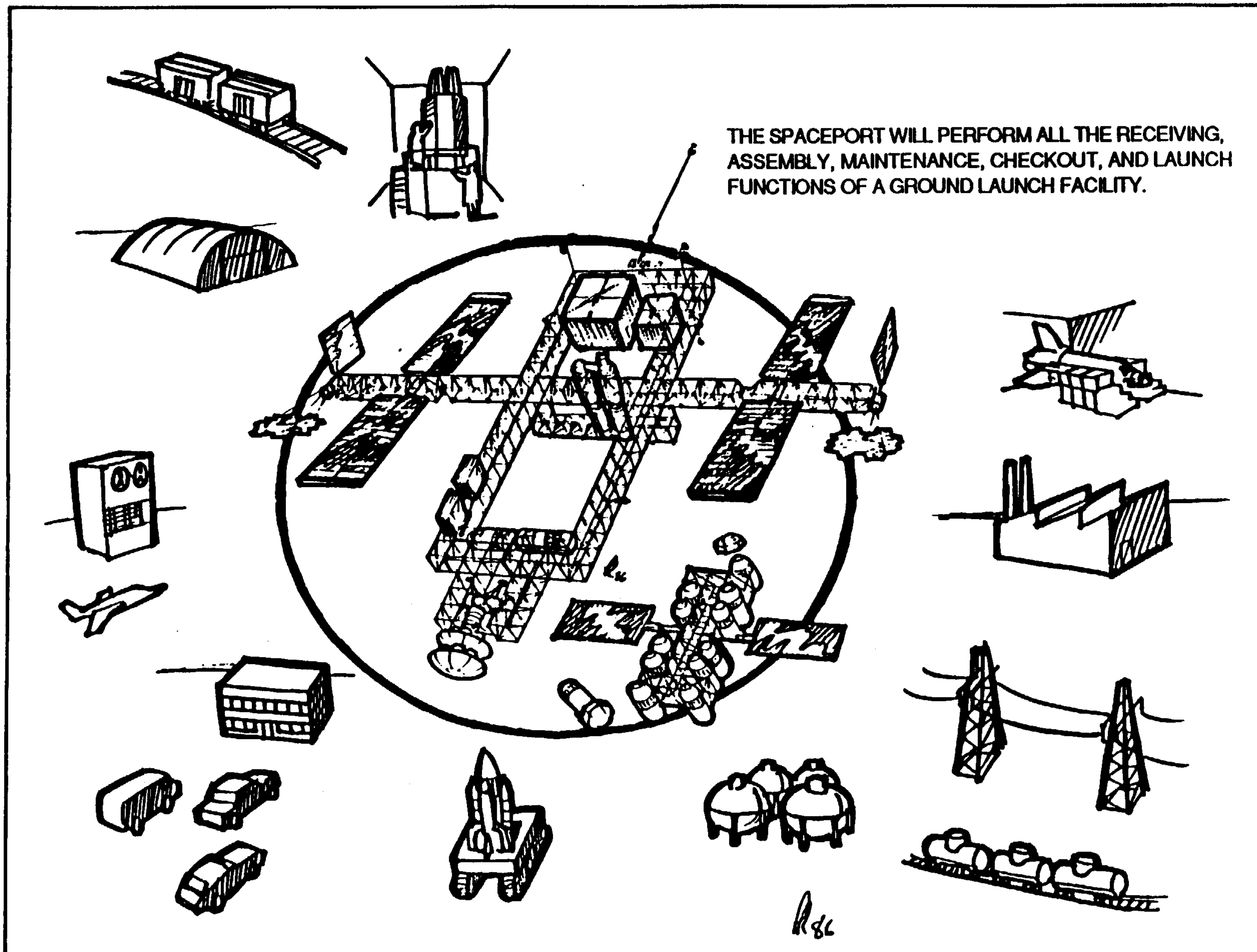
The NCOS report presents a timeline for exploration and habitation of planets. The Space Station, to be established by 1994, will evolve around 2000 into a spaceport through the addition of an orbital transfer vehicle (OTV). An initial lunar base will be set up 5 years later, followed by the first outpost on Mars around 2015.

At the workshop, the lunar and planetary missions team examined the impact of these missions (manned and unmanned) on the Space Station. In particular, it looked at the evolution of the initial operating capability (IOC) Space Station into a full-fledged spaceport functioning in LEO.

MISSION SCENARIOS

The first step toward lunar settlement will be to launch an unmanned remote sensing satellite to lunar polar orbit. Over the course of a few months, sensors of the lunar geoscience observer will collect data on the composition of the Moon. The information returned will yield insights into the origin of the Earth-Moon system and will provide data needed to select a site for the lunar base.

EXHIBIT 4-1
SPACEPORT IN LEO



The site of the lunar base will be chosen according to the objectives of the program, taking into account requirements imposed by the orbital mechanics of the transportation system. If lunar resources are important to the program, the base may be located near sources of target minerals. Radio astronomers may prefer a site on the far side, out of sight of the noisy Earth. A base at the lunar poles would have access to constant solar energy on tors, to constant darkness inside some craters, and possibly to deposits of primordial volatiles in the permanently shadowed regions. If plans call for shipping lunar materials to depots at Lagrangian points using an electromagnetic rail launcher, then an equatorial site would be most convenient. These sometimes conflicting requirements will be resolved in the planning process for the long-term program.

The first buildup missions from the LEO Space Station will take cargo to the lunar base site on unmanned descent stages. A construction crew will follow to assemble the surface elements, which will include habitats, laboratories, and a power plant. At that time, regular Earth-to-Moon service will begin. As lunar activities increase, the mass throughput at the Space Station will also increase. Unless the surface facility develops a capability to use local resources, the LEO transportation node could become a bottleneck, limiting the scope and scale of lunar occupation.

As the lunar base becomes more and more self-sufficient, the tonnage imported from Earth should decrease. Over time, however, this process may be reversed. Once the base becomes self-sufficient, it can grow more efficiently, and the lunar surface population may increase. With a higher population, passenger traffic will rise, and the mass flow from the Earth may increase again.

The human exploration and settlement of Mars will differ from lunar missions in two key respects. First, plans to use martian resources involve some guesswork; there is a lack of information on the physical, chemical, and geological state of the surface. Consequently, unmanned precursor missions may be planned to return samples to Earth. Second, minimum energy trajectories to Mars exist only briefly during the biennial planetary alignment with the Earth. Thus, Earth-to-Mars traffic will be more episodic than traffic between the Earth and the Moon.

A Mars surface sample return (MSSR) mission will take place before manned exploration; in all likelihood, only a few (perhaps only one) of these missions will be undertaken. This mission will probably require mating upper stages and payloads at the Space Station. Assembly of the stack in orbit should not be demanding, but may well be the first operation of this kind at the Space Station.

Eventually, human crews will be sent to the martian surface; but a possible intermediate mission would set up a base on one of the martian moons -- Phobos or Deimos. This scenario has one major advantage: the human payload and its massive life support systems would not have to descend to and be launched from the martian surface. Because the moons have negligible gravity, savings in propellant launched from Earth would be significant.

The first mission to land a crew on the martian surface will establish an outpost. Up to three such outposts may be emplaced, one of which will be chosen to become a permanently occupied base.

When crews are permanently stationed on the martian surface, launches to Mars will take place on regular 2-year windows. Assembling and fueling each spacecraft will take many months, but the Space Station will be unaffected by the mission in the off-time. For this reason, support missions for a martian base are described as episodic.

The Mars space vehicle is assumed to be chemically propelled, to be launched from LEO, and to support the crew over a 2- to 3-year mission. To fill these criteria, the craft must necessarily be large and complex. However, its scale can be reduced if it is launched farther out of the Earth's gravity well (e.g., from a Lagrangian point of the Earth-Moon system). This scenario, however, implies the existence of a spaceport beyond LEO and, in essence, represents a "branching" of the IOC Space Station. Alternatively, if the vehicle were propelled by nuclear power, it could be smaller, and the propellant mass required in LEO would be reduced.

MISSION REQUIREMENTS

Lunar and planetary missions may be categorized in one of three classes, as follows:

- Class I. Preparatory activities, applied science research and technology development (in-space R&T)
- Class II. Episodic assembly/support for single missions
- Class III. Staging/transportation node for recurring or very large scale missions.

Using these classes, it is possible to distinguish between requirements of lunar and planetary missions that will use the station more or less continuously and requirements of those that will use the facilities only occasionally or episodically.

If the Moon and planets are to be explored and settled, we must develop operational skills in space and solve scientific and technical problems associated with space travel and extraterrestrial habitation. The Space Station will provide the first opportunity to attack many of these problems in the space environment. To conduct such research, the Space Station's capabilities and roles must be expanded beyond those now contemplated for IOC.

Class I missions precede spaceport functions and will be part of the early Space Station operating schedule. As experimental procedures attain operational status, some of these activities will no longer be considered research objectives at the Space Station. Consequently, IOC timelines should include a high level of Class I activity for the first decade. As the Space Station becomes more of an operational vehicle and less of a test bed, pure scientific research in space will occupy more of the schedule. However, certain operational questions, particularly those pertaining to life science, will be studied well into the foreseeable future.

The workshop team identified Class I functional requirements for each of 19 technology disciplines and the technology requirements needed to fulfill them. (Technology requirements are shown on Exhibit 7-9 in Section 7 of the report.) Space Station activities considered were those that (1) would be essential precursors to a lunar base and to manned Mars exploration, (2) that could not be adequately carried out on Earth, and (3) that would need the Space Station capability. The team identified a number of functional requirements that will need radically new technological systems.

For example, the Space Station will generate some new information on human responses to the space environment. Once a deep-space voyage becomes a goal, unknowns will become urgent questions. It will be essential to develop and test methods to qualify humans for exposure to gravity profiles and radiation. Experiments to determine behavioral factors of long-duration missions and residual effects after return to Earth will also be needed. Such studies will require a human centrifuge in Earth orbit. They are also likely to require a mammalian centrifuge (e.g., for monkeys) in the Space Station as well as other experimental facilities and instruments.

Life support systems for lunar and martian missions will call for major advances over the life support systems of a LEO Space Station. For the manned planetary missions, high degrees of system closure will be required as a way of avoiding logistics problems. While many of the needed techniques can and should be demonstrated on Earth, some of them must be proven in space. Closed systems should therefore be added to the Space Station's life support capabilities. They may include biological (plant) systems in conjunction with traditional physical/chemical systems. The use of closed life support systems will result in demands for large amounts of input power and waste heat rejection.

If a lunar base is to grow large and contribute to a space-based economy, lunar agriculture will be essential. However, we know little about this field. Scientific investigations will be needed to develop genetically engineered crop plants designed for robustness and high yield under lunar conditions (including 1/6 g). Such studies will require a variable-gravity research centrifuge. This research tool, with appropriate environmental controls and instrumentation, should be a high-priority precursor to a lunar base.

Mars surface sample return missions could be a major precursor activity to manned Mars exploration. Despite the Viking's negative results in the search for martian life, a concern for biological quarantine of a returned sample persists. The Space Station's isolation from the terrestrial environment makes it a good candidate for preliminary study of martian samples. A laboratory module with a biological barrier from the rest of the station will be required. In the unlikely event that an alien pathogen is discovered, the module could be sealed and detached. If the sterility of the martian surface is confirmed, the module could be converted easily to a research facility, possibly for biologically hazardous materials.

Investigations will be needed to answer questions about the long-term physiological effects of zero gravity on humans. A radically new technology will be required to provide artificial gravity in large, manned space systems. To study planetary materials and biological systems under variable gravity, centrifuges and tethered systems will also be required. A research system on board the Space Station may require innovative technology solutions in several areas (Exhibit 4-2).

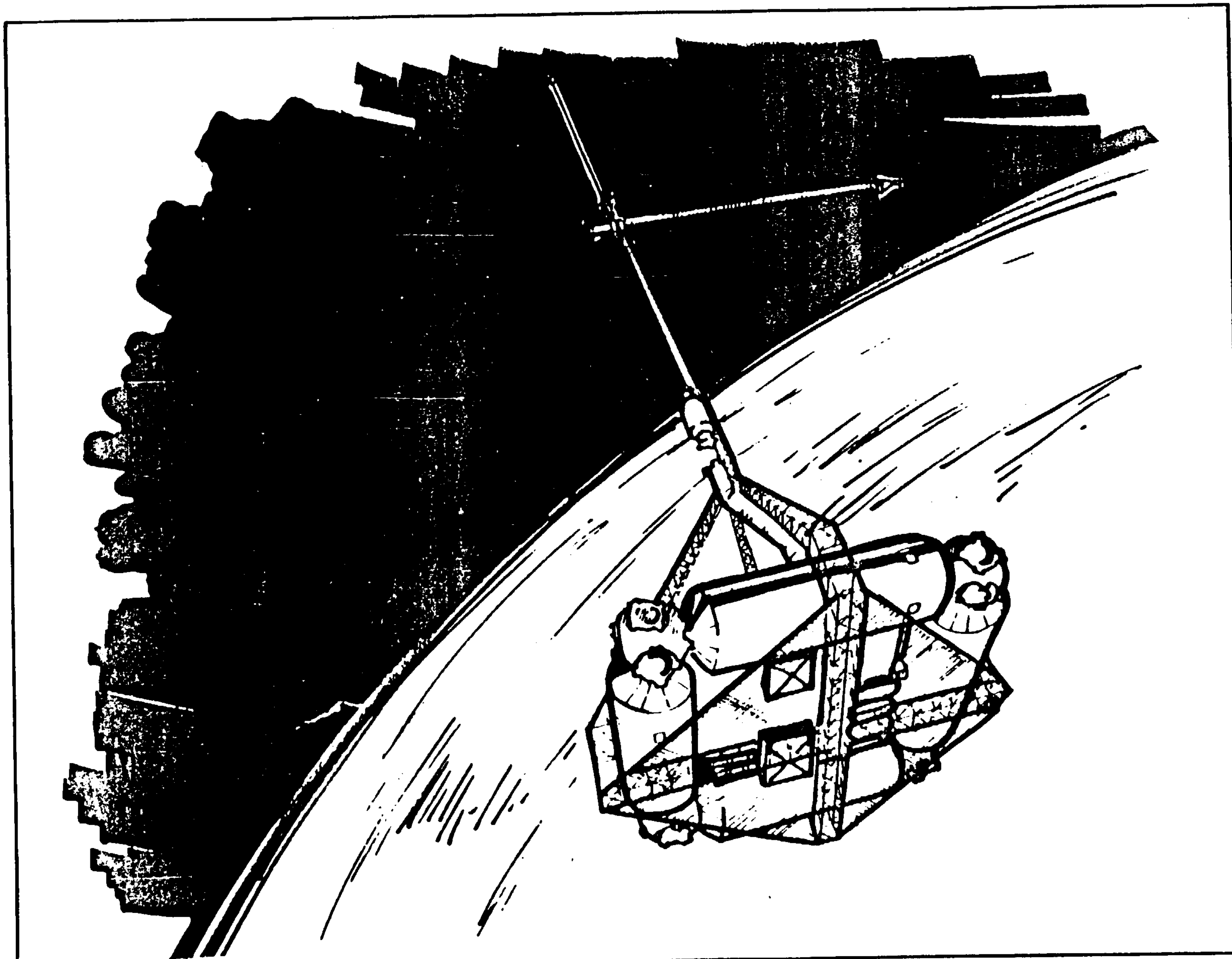
Lunar and martian missions will place a high premium on reliability and maintainability. This could be achieved by designing evolutionary Space Station subsystems to meet requirements for autonomy in these areas. Specifically, real-time expert systems should be emphasized.

Missions to the Moon and Mars will also result in a large increase in traffic through the spaceport. Precursor investigations will be needed to understand the problems of rendezvous, system assembly, and handling very large items, including hundreds of tons of cryogenic liquids stored for long periods.

Lunar and martian missions will be characterized by complex, large-scale, time-critical events that must be executed with small tolerance for error. Much of the required simulation and training can be done on Earth, but some of it must be done in the Space Station to give crews the appropriate experience. Early precursor development of such facilities and procedures on orbit will pay dividends in lunar and martian programs.

ORIGINAL PAGE IS
OF POOR QUALITY

EXHIBIT 4-2
VARIABLE-GRAVITY RESEARCH FACILITY



Class II missions will occur for a limited time at regular intervals. Typical missions in this class will support manned Mars exploration and settlement, but high-energy, unmanned planetary exploration launches also fall into this category.

A study conducted by NASA and by the LANL ("Manned Mars Mission") documents the high level of activity to be expected for a launch from LEO. According to estimates, the departure mass for an all-propulsive design using cryogenic fuels will be be 1,620 metric tons, of which 1,440 metric tons will be propellant. A similar design using storable fuels has been rejected as too massive. If aerobrakes are used both on Mars and on return to Earth, the LEO departure mass will be 713 metric tons, of which 550 metric tons will be cryogenic propellant. By comparison, the IOC Space Station is estimated to have a mass of 230 metric tons.

The core Space Station program shows that the payload delivery and servicing mass will grow over a 6- to 8-year period to a steady state of 400 to 500 metric tons per year. Thus, in an ongoing program, the smaller of the two Mars vehicles will require an Earth-to-LEO launch capacity equal to 18 months of Space Station support, repeated every 2 years. Two vehicles will be necessary because the first one will not return in time to be reused for the second mission. The first vehicle will be maintained, refurbished, and stored (possibly as a free-flyer) until the next mission. As this estimate for Earth-to-orbit support is based only on the spacecraft mass, additional launches will be required to ferry construction personnel and interplanetary crews.

For the manned Mars missions, optional modes of handling systems at the Space Station should be considered in three functional areas -- assembly/checkout, tanking/departure, and return/capture. Tanking, in particular, is an activity that should occur away from the Space Station. The 550 metric tons of propellant could be moved much more efficiently from an Earth-to-orbit tanker directly into the Mars vehicle than from enlarged storage tanks on the Space Station. Because fueling should be done just prior to departure, the Mars vehicle, if attached to the Space Station, could be removed before increases in the large mass (and hazard) associated with tanking occur. Thus, control and safety of the station would be increased.

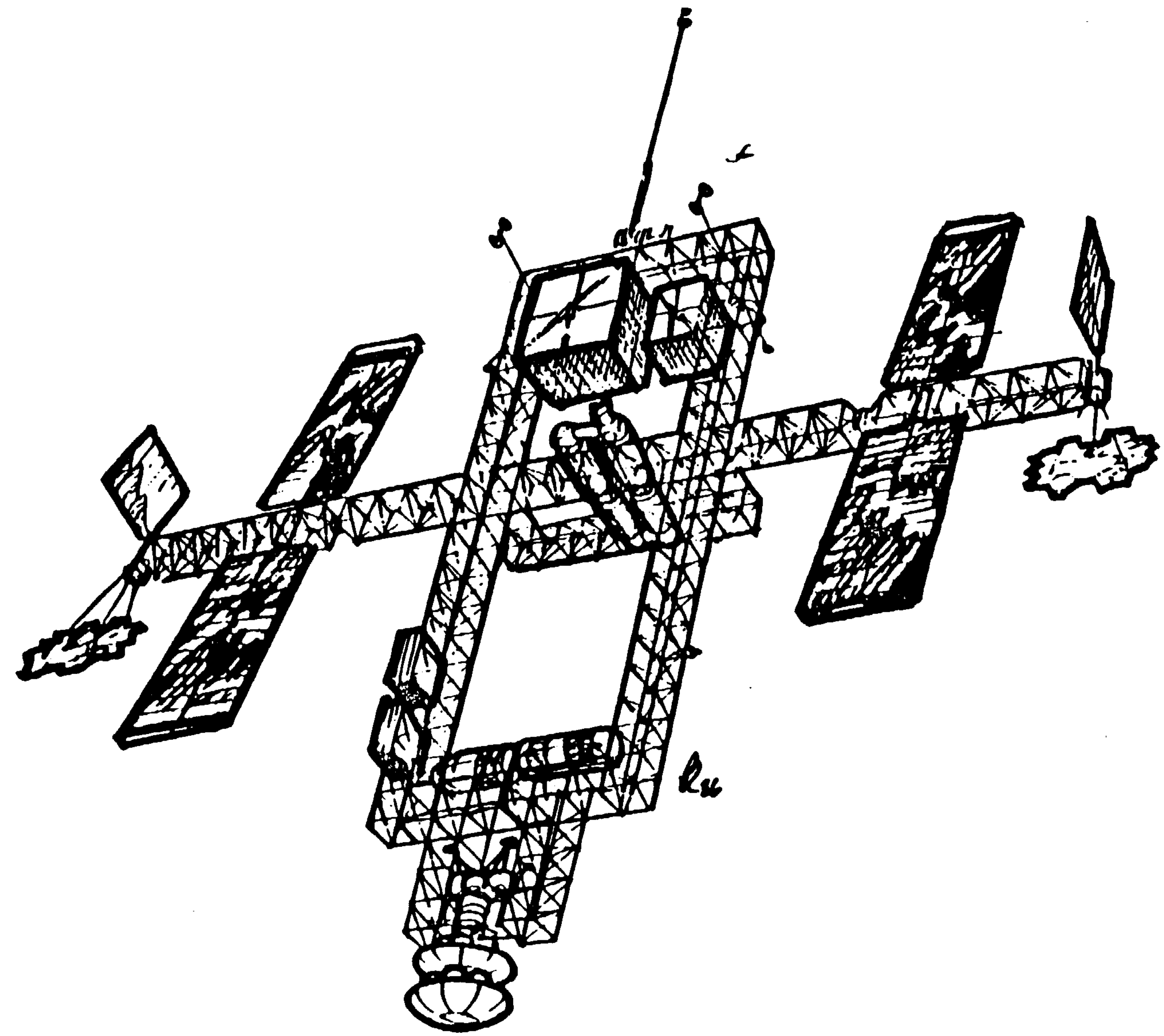
Class III missions include lunar base buildup and support. For these missions, launch windows to the Moon will be so frequent that the mass flow through the LEO spaceport will be essentially continuous. The mass flow to LEO could run between 450 to 900 metric tons per year. (The variation from year to year will depend on the buildup sequence assumed.)

A good picture of the level of activity for Class III missions can be obtained from a summary description. During the decade modeled, the Space Station will support 68 lunar sorties, 43 of them manned. Each sortie will require two AOTVs, both of which return to the station. To support lunar sorties, 102 Earth launches will be needed, half of them Shuttles and half of them unmanned Shuttle-derived vehicles (SDVs) capable of delivering 100 metric tons of cryogenic propellant to LEO. If the SDVs must be replaced by Shuttle launches, then 255 Earth launches will be required over the 10-year period -- three times the number required to support the Space Station in the core program model. Additional habitat modules will be required to billet from four to six transient lunar base personnel. Other facilities required for a spaceport function are given in Exhibit 4-3. A configuration for this function is shown in Exhibit 4-4.

EXHIBIT 4-3
SPACEPORT FACILITIES

- Protective hangars for spacecraft
- Checkout, assembly, and launch
- Capture and retrieval of spacecraft and returning payloads
- Proximity operations
- Propellant transfer
- Propellant depot
- Transient habitation
- Reactor handling
- Warehousing of payloads
- Power capacity above IOC levels
- Quarantine module for returned planetary samples
- Centrifuges and/or tethered systems (variable gravity)
- Ecosystem experiment facilities

EXHIBIT 4-4
SPACE STATION ACCOMMODATION OF AOTV MAINTENANCE AND DEPOT FUNCTIONS



OPTIONS FOR SPACE STATION EVOLUTION

Because lunar and planetary missions will involve large mass motions on the Space Station structure, an extensive program of such missions will eventually be incompatible with an active microgravity program. There are two major avenues by which program evolution can accommodate both of these programs:

- The Space Station could evolve to a specialized spaceport, with microgravity science branching to separate, quiet platforms or manned elements as processing and research needs dictate (Exhibit 4-5). Other sciences could be accommodated similarly. Research at the station would be limited to motion-insensitive experiments and the use of massive, autonomously pointed observation instruments.

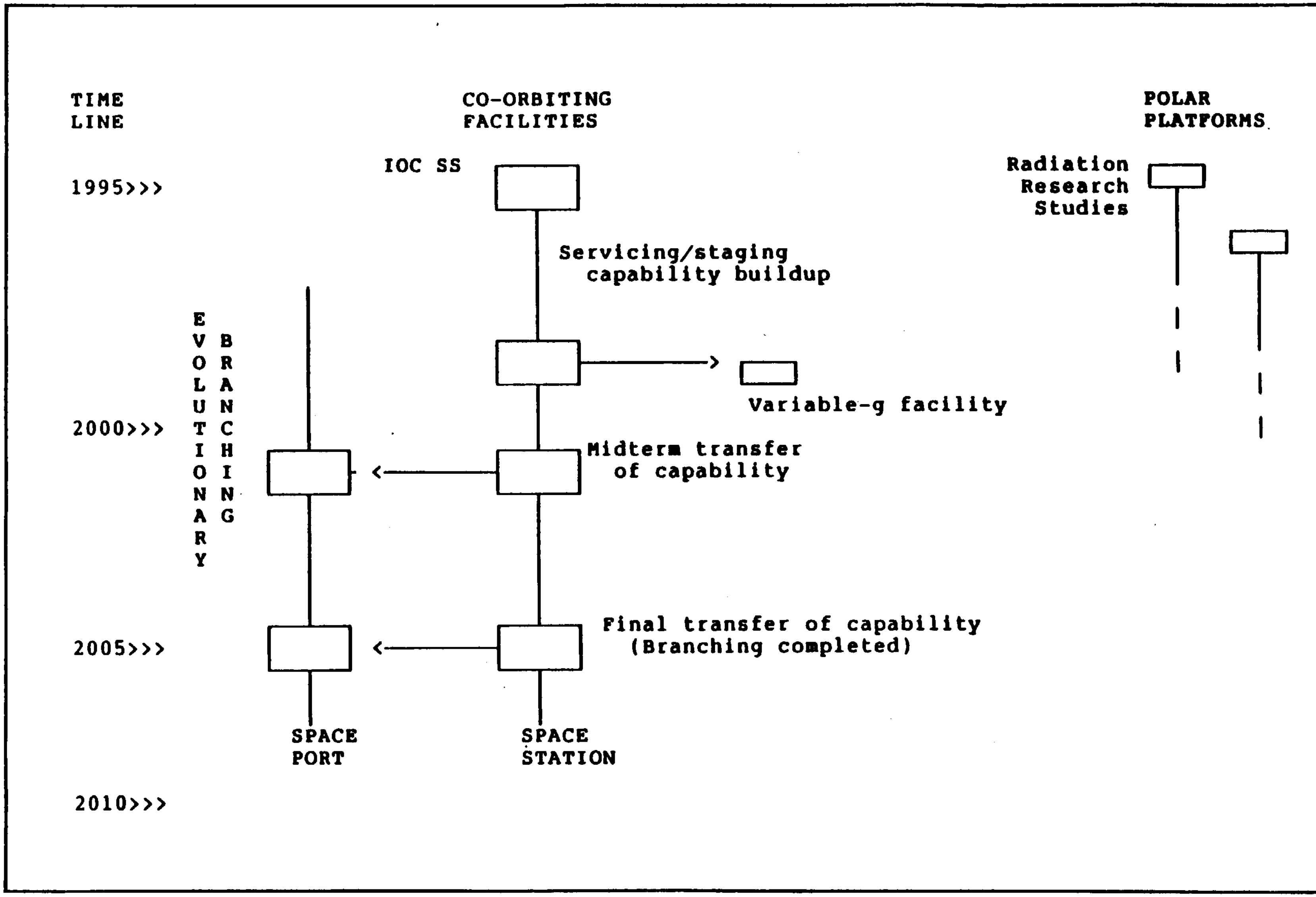
- The Space Station could evolve to a new spaceport when the lunar and planetary mission activity becomes too disruptive to other science and manufacturing activities.

Both approaches are compatible with the present manned baseline.

REQUIRED TECHNOLOGY

Performance capabilities of the manned systems for a lunar base or a manned Mars mission will need to exceed the performance of many technological systems currently in the research stage. Thus, a wide range of technological advances will be needed to enable such missions. Many technologies will probably be pursued on the Space Station in its role as a broadly based user facility. However, technology areas requiring significant performance increases or fundamentally new systems will require special attention. (Technology

EXHIBIT 4-5
SPACEPORT BRANCHING SCENARIO



requirements and tall poles for lunar and planetary missions are listed on Exhibits 7-9 and 7-10 of Section 7.)

One critical requirement is transportation. Low-cost access to LEO and a space-based OTV that can go to lunar orbit will be essential.

A second critical requirement is for a spaceport or "shipyard" function at the Space Station. Staging areas for assembly, vehicle servicing, and propellant transfer and storage will be needed. The activities of this function will increase with the number of lunar and planetary missions, eventually consuming most of the station's resources and causing contamination and dynamic disturbances that will interfere with other station uses.

A third critical requirement for lunar and planetary missions is ecosystems technology. Studies will be needed of the physiology of humans and biological science of plants and animals. Plants must be developed for lunar agriculture. Facilities must be available to quarantine planetary spacecraft and returned samples. Completely closed life support systems will be needed, perhaps using plants for air regeneration and food production as well as waste processing.

A fourth critical requirement is for artificial gravity systems. Humans in zero gravity for more than 6 months may undergo unacceptable physiological changes, such as calcium loss from bones. If these cannot be countered through exercise or pharmacology, long-duration spaceflight may require rotating or revolving systems to provide artificial gravity. Virtually all technology disciplines -- fluid management, communication, proximity operations, structures, and mechanisms -- will be affected by such systems. Centrifuges or tethered systems will be required for physiological tests and planetary agriculture and materials processing experiments. These systems will also have a profound impact on station operations.

A fifth critical requirement is for long-life autonomous operation of lunar and planetary systems. Mission systems must remain reliable and maintainable for years. Real-time expert systems will be needed for self-diagnosis and repair, contingency planning, and scheduling. All systems must be radiation tolerant.

RECOMMENDATIONS

The NCOS's vision of our next 50 years in space includes spaceports as an essential element of the space program. The IOC Space Station, which will provide permanent manned presence in space, is a logical step toward establishing a spaceport capability to support lunar and planetary missions.

The IOC Space Station's role as a spaceport should be given greater priority and visibility. The systems and technologies associated with lunar and planetary missions require further definition. The spaceport requirements and functions of the IOC Space Station should be studied in association with its other roles.

Staging capability should be incorporated early into the IOC Space Station. Planned and projected scientific missions to the planets and the Moon will require on-orbit assembly and some spaceport functions. Scheduling to meet these missions needs must be traded against the implementation and development schedule for the IOC Space Station. The objective of early incorporation is to achieve synergism between scientific and demonstration missions and the evolution to spaceport capability. The spaceport role will be essential to achieving low-cost transportation, which in turn will be crucial to the development of space.

Studies should be conducted of branching options and associated tradeoffs for all Space Station objectives. This recommendation follows from the evolutionary schedule and capability requirements for spaceport functions. Spaceport requirements will be early but intermittent until low-cost, greater capacity, Earth-to-orbit transportation is available. At that time, sustained spaceport operations will be needed. Thus, the branching options for spaceport functions are inherently an evolutionary process.

The initial Space Station must include a rudimentary spaceport capability to support Shuttle docking. Assembly and checkout of unmanned, high-energy planetary exploration missions can also be done in facilities attached to the main station. Payload masses will not be so great as to upset the center of mass of the station, and the frequency of the launches will be low enough to favorably schedule sensitive long-term experiments.

The addition of space-based OTVs will affect the station dynamics and environment. The two OTVs for a lunar sortie will weigh 7 tons each and will be able to hold 42 tons of cryogenic propellant. The movement of this much weight around the station can cause mass management problems. Pumping the propellants may be hazardous. One solution to these problems might be a co-orbiting tank farm where refueling can take place. Thus, a spaceport might evolve in which some functions would not be attached, but would keep with the main station structure in a common orbit.

High launch rates from the spaceport will make the structure dynamically active and may contaminate the immediate orbital environment with effluents. To avoid conflicts between uses, some research functions requiring stable microgravity or an optically benign environment could be moved away from the transportation function. The facilities would be separated

spatially but would still co-orbit to allow easy movement from one to the other. Thus, a third mode of growth might be called the co-orbiting free-flyer.

Some platforms will operate independently of the main station in distinct orbits. However, the main station may still provide services such as maintenance or data links. Some functions that were part of the initial configuration may be moved to independent platforms once the operation matures beyond an experimental mode. Part of the transportation function might be moved out of LEO to depots at Lagrangian points or in lunar orbit. Thus, several types of evolution strategy can lead to a fourth mode consisting of independent free-flyers.

The impact of Class I missions on the IOC station will vary. On the one hand, dedicated laboratory modules needed for life science research will interface with the resources of the facility just as other dedicated research projects do. The mass flows, power levels, staffing needs, and volumes need to be defined but are not unique. On the other hand, life science studies will eventually include variable-gravity experiments, and the centrifuges used will affect station dynamics.

Many facilities and tools needed for performing the activities of Class II and III missions will not be part of the initial configuration. Therefore, designers must allow for addition of maintenance bays, tank farms, warehouses, and robotic machinery under telecontrol.

The needs of lunar and planetary programs would be best satisfied with a Space Station dedicated to "transportation node" functions (or at least to "operations" functions). However, lunar and planetary programs would certainly benefit from the availability of a multidiscipline Space Station. The impacts of lunar and planetary activity on such a station can be minimized by the modes of operation (attached, co-orbiting, etc.) selected.

5. MICROGRAVITY TEAM REPORT

5. MICROGRAVITY TEAM REPORT

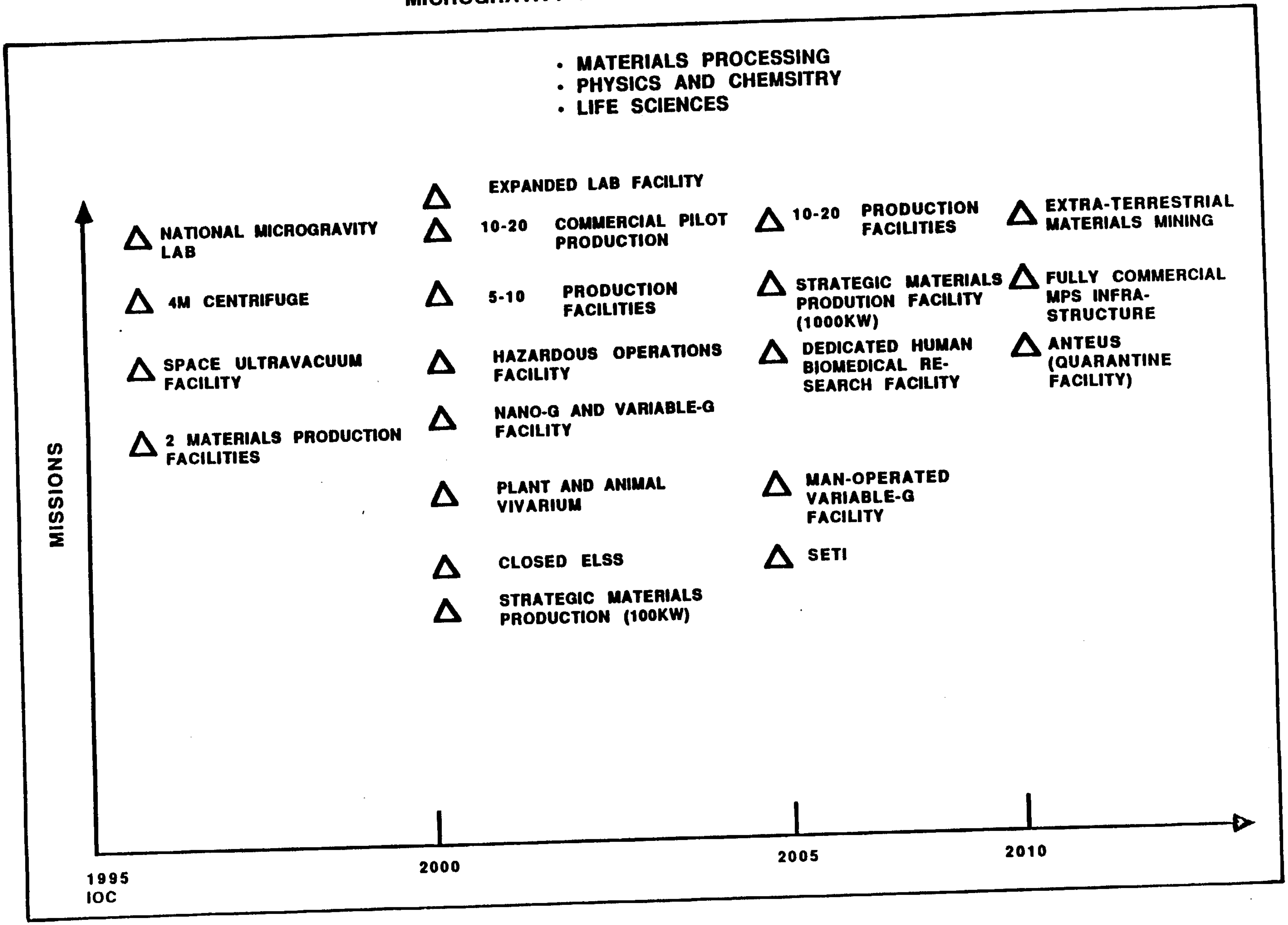
The microgravity team included members from three disciplines: materials processing in space, microgravity science, and life science. Materials processing includes research in and commercial production of materials in space. Microgravity science includes fundamental chemistry and physics research under reduced-gravity conditions. Life science includes experimental research on the adaptability of plants, animals, and humans to the space environment.

MISSION OBJECTIVES

The first goal of the materials processing and microgravity science disciplines is to develop a comprehensive research and development program by 2000-2005. As shown on Exhibit 5-1, microgravity research will begin with Space Station initial operating capability (IOC). A national microgravity research laboratory will be available at that time with facilities for processing electronic and electro-optical materials, metals and alloys, glasses and ceramics, polymers, and composites. Facilities for biotechnology, combustion, fluids, heat transfer, chemistry, and physics experiments will also be available.

Some commercial production will take place in the early Space Station. Full-scale materials production will evolve between 2000 and 2010, first on the core Space Station, then on attached modules and co-orbiting free-flyers, and finally on large free-flying factories. By about 2010, a fully commercial infrastructure is expected to be developed. This infrastructure will consist of factories and associated subsystems, including structures, propulsion, communications, automation and robotics, power, waste management, and thermal management systems. Privately owned and operated, it will also include facilities

EXHIBIT 5-1
MICROGRAVITY MISSION REQUIREMENTS



for transportation, logistics, maintenance, and servicing. If by 2000 a strong demand for strategic materials develops that can be satisfied only by space-based production, this schedule can be accelerated. The demand for space-processed materials could exceed 1000 tons per year. To meet this demand, custom-made factories powered by large nuclear power reactors will be required.

The long-range goals of the life sciences program are to understand the effects of gravity on biological functions, to prepare for long-duration manned space missions, and to explore the origins of life in the universe and on Earth. A manned laboratory will be in place at IOC for studing biological systems. The Space Station will evolve to accommodate fully closed ecological systems and experimental systems that allow gravity levels to be treated as a variable experimental parameter. Preparing for long-duration manned missions will require studies of plants for food production and of animals as human models. Studies will eventually be conducted with human subjects in facilities with variable gravity. Exploring the origins of life in the universe will require instruments to examine dust collected from the inner solar system and to search the universe for signs of extraterrestrial intelligence. Facilities to quarantine material returned from lunar and martian exploration will also be needed.

MISSION REQUIREMENTS

The microgravity program mission requirements are shown in Exhibits 5-2, 5-3, and 5-4. These requirements primarily reflect the missions identified in the existing data base (compiled several years ago but updated periodically). They also reflect several recently developed concepts (e.g., the space ultravacuum research facility and the large superconducting magnet crystal growth facility). Because it is difficult to project accurately even a few years ahead -- and

EXHIBIT 5-2
MATERIALS PROCESSING MISSION REQUIREMENTS

	Year Required	Power - kW Avg	Power - kW Peak	Crew MH/Day (Avg)	Volume/ Double Racks	Thermal kW	Type
MPS Lab (COMM 1201/1204, SAAX 401)	1995	58	70	1	40	60/75	R&D
	2000	58	70	1	40	60/75	R&D
			(Pressurized Module)				Pilot/Prod.
EOS Units (COMM 1202)	1995	3.5	15	2	4	3.5/15	Prod.
	1997	3.5	15	2	4	3.5/15	Prod.
	1999	3.5	15	2	4	3.5/15	Prod.
			(Attached Pressurized Module)				
ECG Units (COMM 1203/1205)	1995	27	27	1	4	27	Prod.
	1998	27	27	1	4	27	Prod.
	2001	27	27	1	4	27	Prod.
			(Pressurized Module)				
Biological Unit	1997	20	26	2	4	20/26	Prod.
			(Attached Pressurized Module)				
Crystal Unit	1998	32	39	2	4	32/39	Prod.
			(Pressurized Module)				
Containerless Process Unit (COMM 1213)	1998	10	10	2	4	10/10	Prod.
			(Pressurized Module/External Unpressurized)				
Vapor Crystal Growth Unit	1995	10	15	2	1	10/15	Prod.
	1998	10	15	2	1	10/15	Prod.
			(Pressurized Module)				
Isolation/Hazard Operation Facility	2000	10	15	1	Short Module	10/15	R&D/ Prod.
			(4m Superconducting Magnet)				
Space Ultravacuum Research Facility	1995	2	5	1	N/A	2/5	R&D/ Prod.
	(Man-tended free-flyer/dock at berthing port/OMV Serviced)						
Strategic Material Production Facility	2000	100/	100/	1	40	100/1000	Prod.
	2005	1000	1000				
	(Man-tended station - derived free-flyer W/SP-100 class reactor)						

EXHIBIT 5-3
PHYSICS AND CHEMISTRY MISSION REQUIREMENTS

	Year Required	Power - kW Avg	Power - kW Peak	Crew MH/Day (Avg)	Volume/ Double Racks	Thermal kW	Type
MTL Lab (SAAX 401)	1995	2	5	- 4	4	2	R&D
Variable Gravity Facility	2000	1	1	2	N/A	1	R&D
		(Free-flyer or tether)			(10^{-3} to 10^{-6}g)		
Nano-g Facility	2000	0.1	0.1	0.1	N/A	0.1	R&D
		(Free-flyer, liquid helium)					

EXHIBIT 5-4
LIFE SCIENCES MISSION REQUIREMENTS

	Year Required	Power - kW Avg	Power - kW Peak	Crew MH/Day (Avg)	Volume/ Double Racks	Thermal kW	Type
Life Science Reference	1995	15	20	12	31	15/20	R&D
		(Pressurized Module)					
4m Centrifuge	1995	0.5	2	1	8	1	R&D
		(Pressurized Module)					
Plant and Animal Vivarium	2000	2	3	4	20	2.5	R&D
		(Pressurized Module)					
Closed Ecological Life Support System	2000	10	15	8	20	10/15	Tech. Dev.
Exobiology Collector	2000	0	0	0.1	N/A	0	R&D
		(Attached Payload)					
Radiation Studies	2000	0.5	0.5	0	N/A	0.5	R&D
		(ESA Package on Polar Platform)					
Man-Rated Variable Gravity Facility	2005	10	12	48	40	10	R&D
		(Tethered Pressurized Module)					
SETI	2005	1	1	0.1	N/A	1	R&D
		(Free-flying large antenna)					
Anteus	2010	2	3	1		2	R&D
		(Pressurized free-flyer)					

impossible to do so 10 to 25 years ahead -- most of these mission requirements are generic rather than specific. However, they reflect the direction the program is expected to take.

Teledyne Brown Engineering Company and Boeing Aerospace Company are in the process of completing a study to identify the facilities, power, crew time, logistics, and support equipment needed for experiments now in the data base and for those that have recently been identified.

The study identified 30 facilities needed for materials science and physics and chemistry experiments. These facilities will require 44 double racks to house them. The problem in meeting this requirement is that the present lab configuration makes only 20 double racks available to experimenters; thus, only about half of the required facilities can be accommodated at IOC. (Rack space may not be a problem at IOC, however, as budget and other constraints may limit the number of facilities available at that time.)

The situation for life science experiments is similar, except that it is not yet clear where they will be accommodated. The life science community has also identified several additional attached modules that will be required later (e.g., a plant and animal vivarium, a closed ecological life support system). The basic problem is that each group of experiments could easily fill an entire lab module by IOC. In addition, the user base is expanding and new concepts are evolving rapidly. Thus, the rack requirements projected for life sciences research must be viewed as conservative.

One solution to the rack-space problem would be to change out racks as experiments are completed. However, this raises the problem of what to do with the racks that have been replaced. Taking them back to Earth is prohibitively expensive if they need to be brought back up again. Some storage might be made available, but valuable crew time would be taken up in changing out racks of equipment. In addition, other experiments would be disturbed. It may be most feasible to leave equipment with future use in place and to bring up a new module.

The Teledyne Brown study identified a relationship between power requirements and crew time. Only 20 kW average power will be required for the first sets of experiments -- a level compatible with power available at IOC. However, at this level, the number of manual operations will limit the complexity and number of experiments. Therefore, a requirement for greater automation can be expected as the Space Station evolves. Such automation will, in turn, increase the power requirement; if the process for changing samples were automated, for example, the IOC complement could easily consume 60 kW average power. Power demand will increase further as more semiautomated, power-intensive commercial pilot operations (such as Microgravity Research Associates' electroepitaxial crystal growth) are supported.

It has been recognized only recently that superconducting magnets will be required in conjunction with microgravity to suppress buoyancy-driven convection in large-diameter (10 to 30 centimeter) melts to achieve diffusion-controlled growth. If such growth conditions are beneficial, magnets will be indispensable for scaling various crystal growth processes up to commercial requirements. This activity will require a supply of liquid helium, a safety vent, and magnetic shielding.

Special isolated areas will be needed for handling hazardous substances used in materials processing and life science activities. Such areas will also be useful for isolating facilities such as the large superconducting magnet and the 4-meter centrifuge. They could also be used for P-4 class biological isolation for quarantine or other activities. Concepts of these modules are shown in Exhibits 5-5 and 5-6.

Requirements for controlled-gravity facilities have also begun to emerge. Studies in gravitation relativity and critical-phase transition phenomena will require substantially lower gravity levels than can be achieved practically on the station. Hence, a free-flying nano-gravity facility will be required. For studies of scaling laws in fluid processes, a variable-gravity facility in which acceleration can be controlled over a range from 10^{-3} to 10^{-6} g will be needed. A manned laboratory in which gravity levels can be varied from 10^{-6} to somewhat greater than 1 g, as shown in Exhibit 5-7, will also be required for life science research.

The materials processing community has identified other needed free-flying facilities. A wake-shield vacuum facility, as shown in Exhibit 5-8, can provide contamination-free 10^{-14} torr equivalent pressure even in the presence of high heat loads. Such a facility will be used for research on the growth of controlled-microstructure materials, such as superlattices, by molecular beam epitaxy. Further, if it can be shown that the quality of strategic materials can be enhanced by processing in microgravity, there will be a strong push for a man-operated, free-flying production facility with very high power capability, perhaps as high as 1 MW. Exhibit 5-9 shows such a facility powered by an SP-100 class reactor.

The team identified the following as major requirements for conducting microgravity activities:

- At least four free-flying facilities (not sta dard platforms) will be needed. These will require an orbital maneuvering vehicle (OMV) for deployment and retrieval. Several of these facilities will require docking to an airlock for servicing.

EXHIBIT 5-5
ISOLATION MODULE CONCEPT

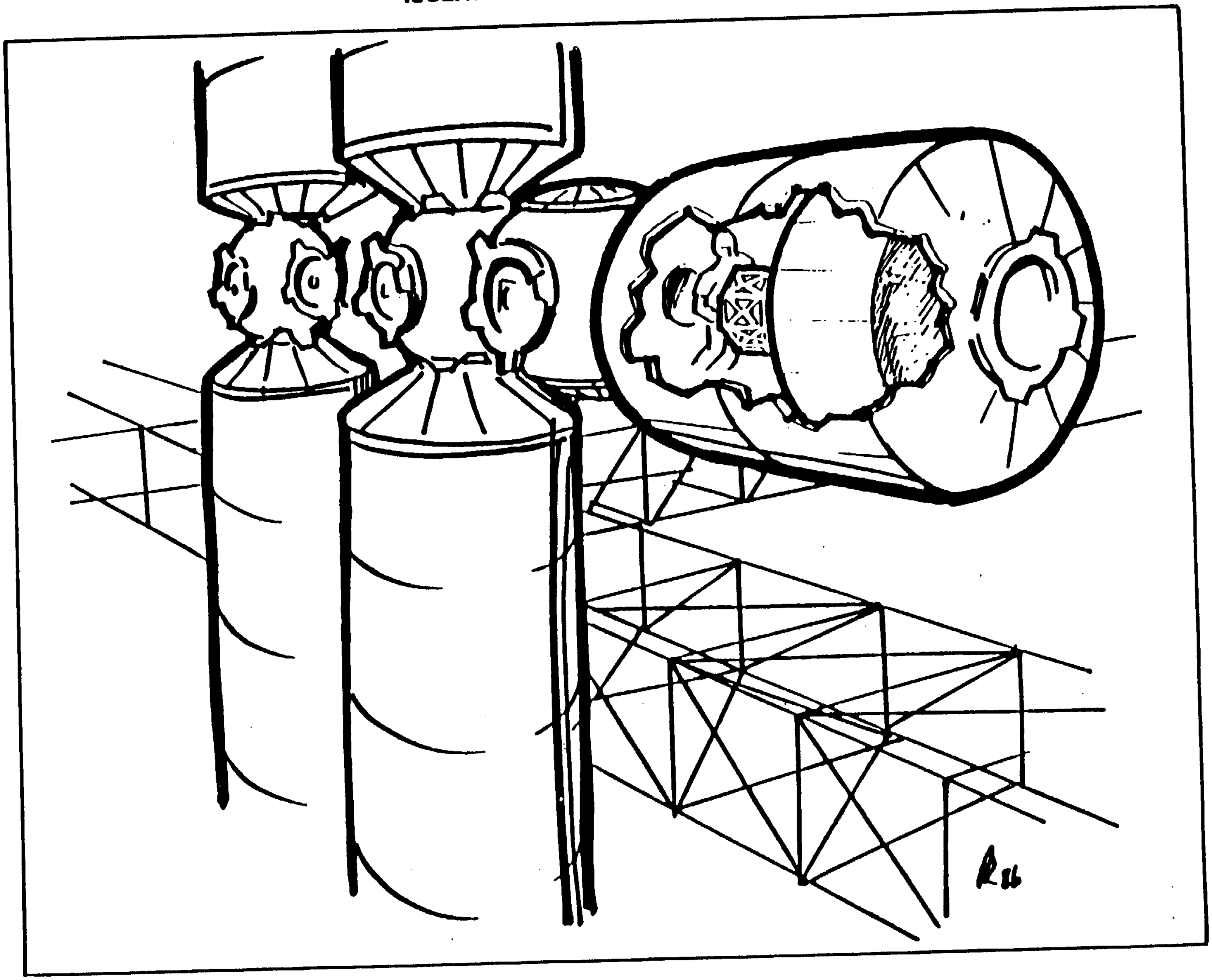


EXHIBIT 5-6
ISOLATION MODULE CONCEPT

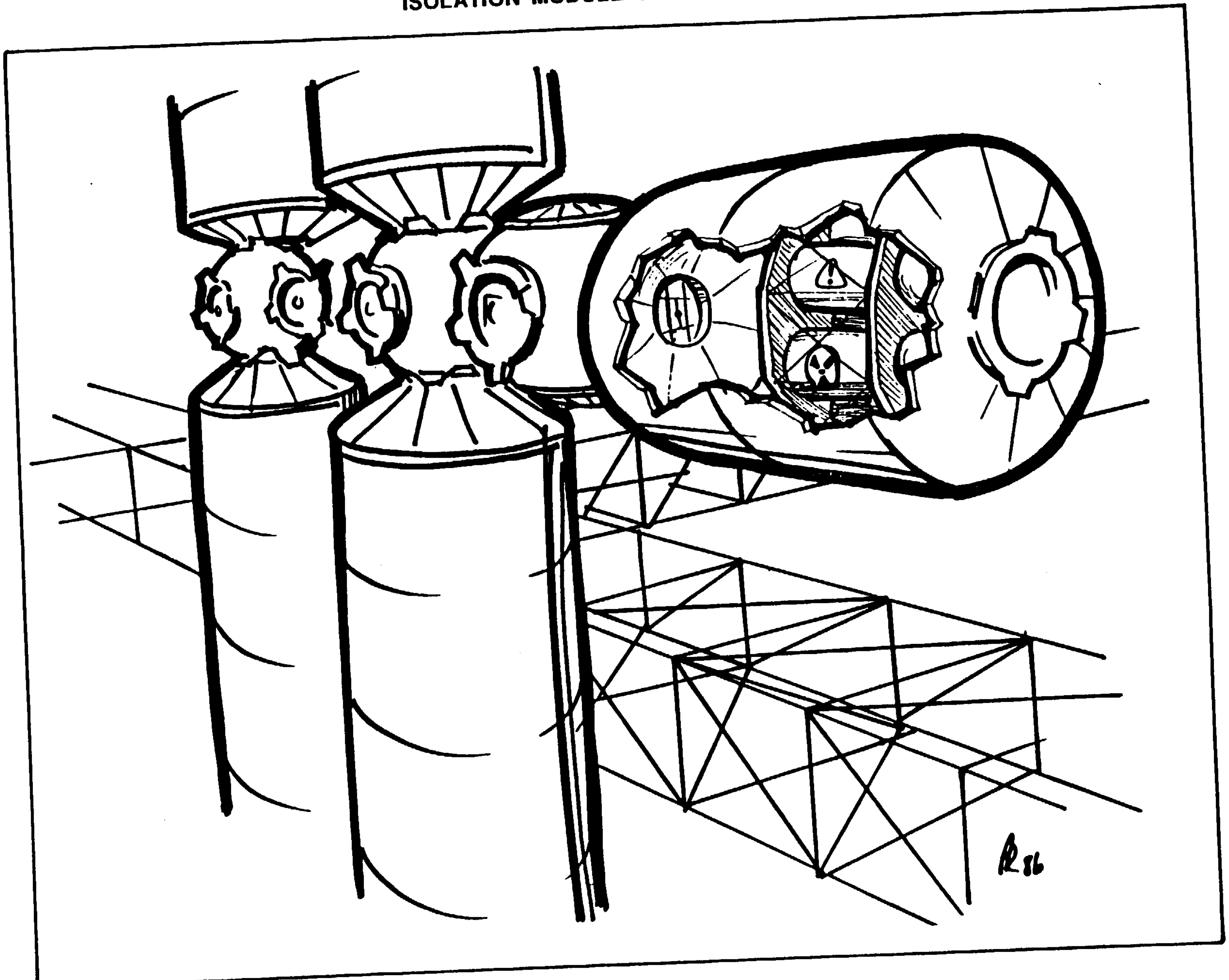


EXHIBIT 5-7
MANNED VARIABLE-GRAVITY LABORATORY

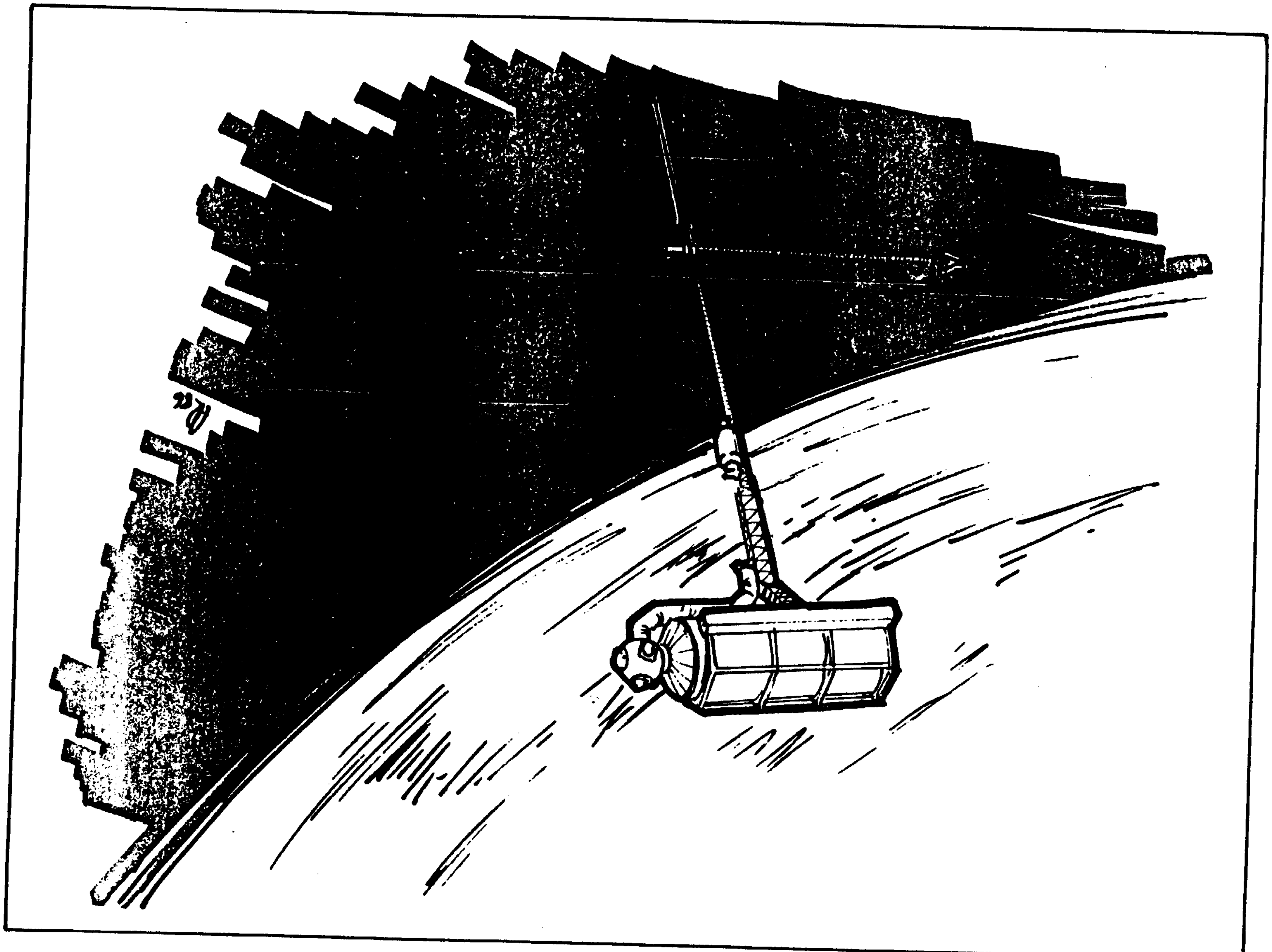
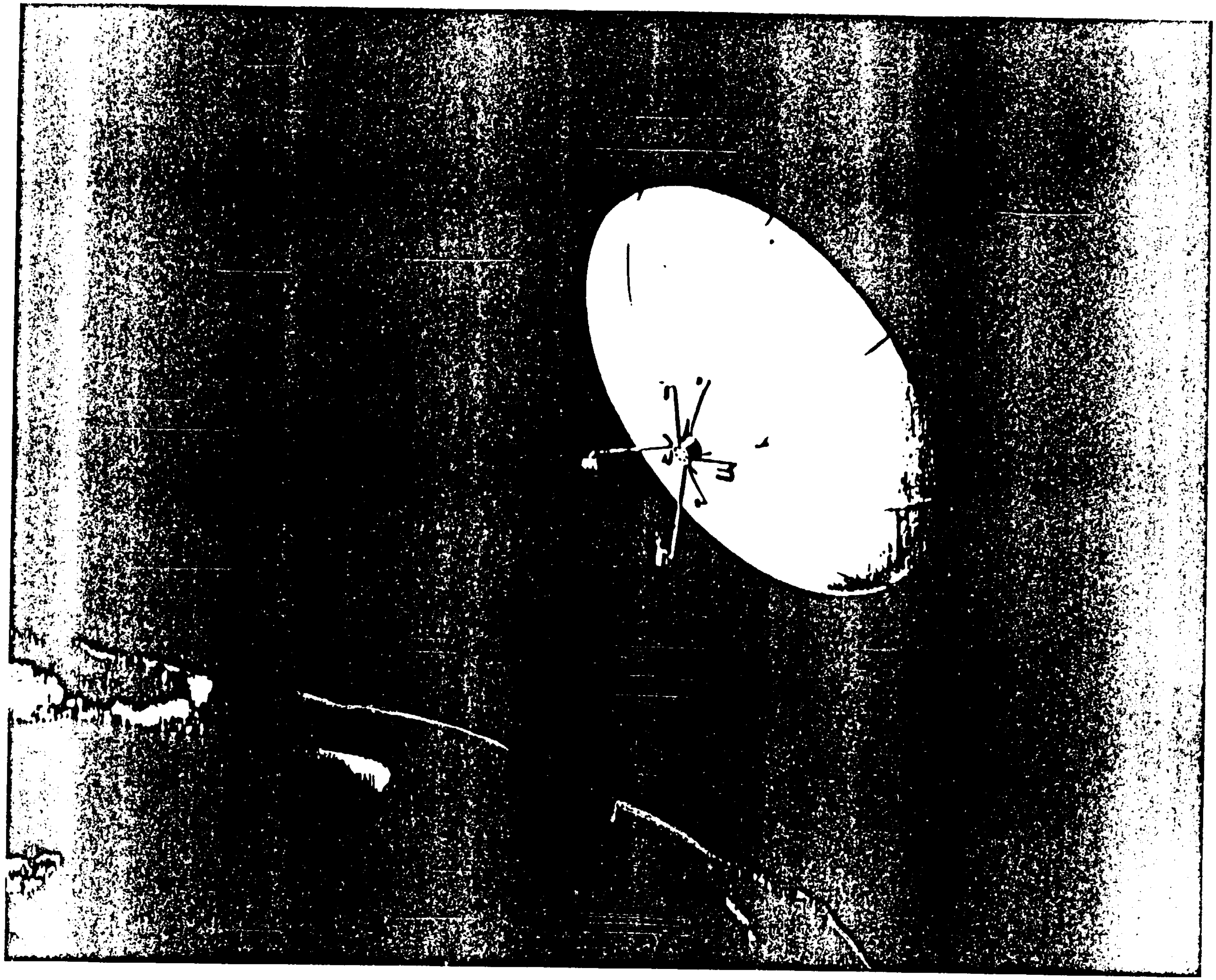
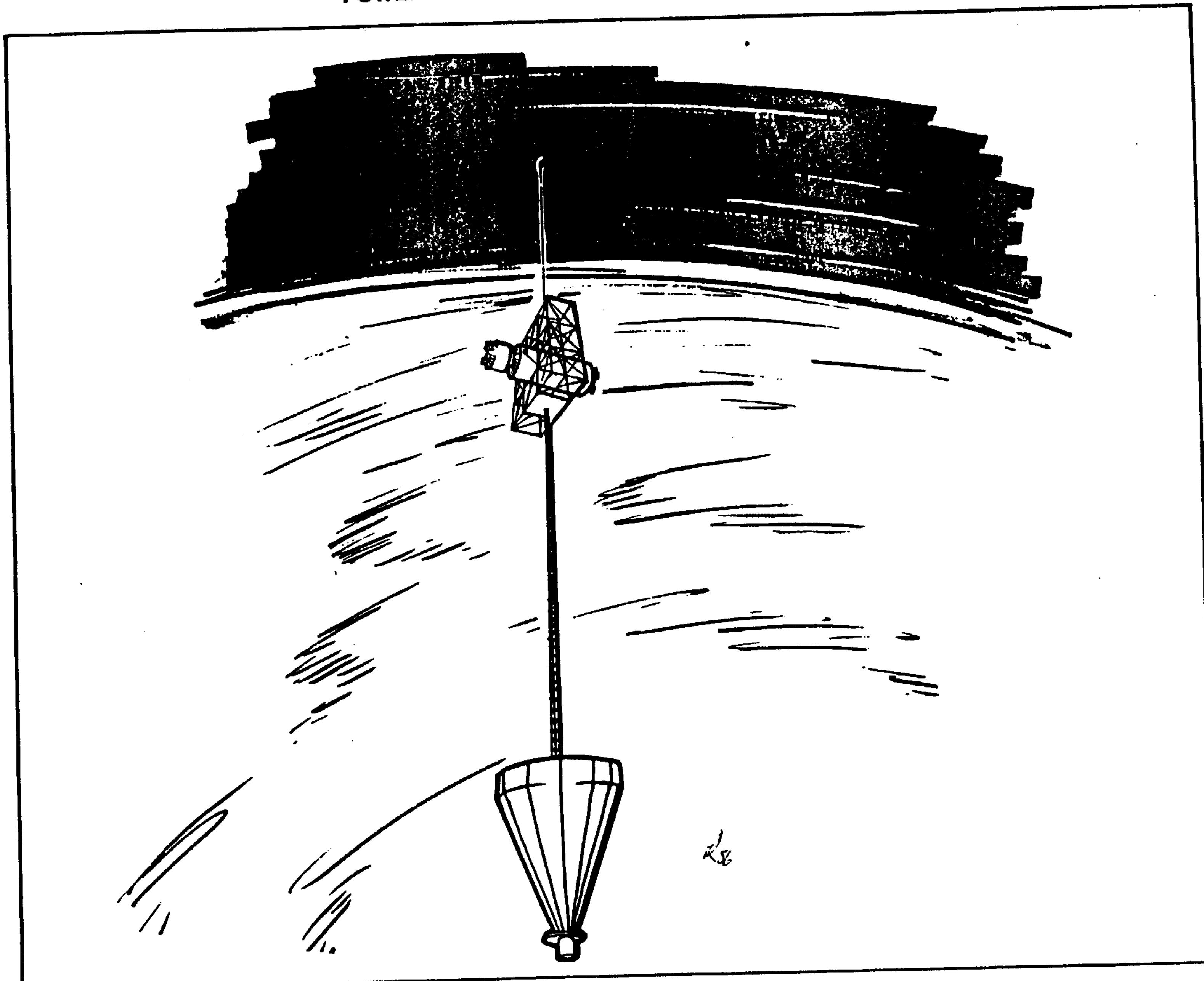


EXHIBIT 5-8
WAKE SHIELD VACUUM FACILITY



CD2

EXHIBIT 5-9
MAN-OPERATED, FREE-FLYING PRODUCTION FACILITY
POWERED BY SP-100 CLASS REACTOR



- At least four isolation/hazardous operation facilities will be needed. These must be attached to airlocks at ports in the nodes.

- A sustained < 10^{-6} g unidirectional acceleration environment will be required for periods up to 60 consecutive days.

- Some overboard venting of gases will be required. These gases will be restricted to those naturally occurring in the Space Station environment. The amounts vented will disturb the column density less than 1 percent in any direction.

- High-resolution color video downlink will be required for short periods of time. Standard format video uplink will also be required for occasional use. Two-way voice links to individual crew members from experimenter/commercial sites will be required on a continual basis.

- Late/early access to a logistics module (or other cargo carrier) will be required.

- Rapid sample return will be needed.

- Launch cost to LEO must be drastically reduced. The target should be $100 per pound delivered to the station.

REQUIRED TECHNOLOGY

The technologies required for microgravity missions include traditional disciplines already part of the station advanced development program: attitude control, automation and robotics, communications, data management, environmental control/life support systems, extravehicular activity, fluid management, manned systems, materials, mechanisms, power, propulsion, structures, thermal, assembly, servicing, and space facilities. (These technologies and the major technology drivers for development of the expanded station are shown in Exhibits 7-11 and 7-12 in Section 7 of this report.) Recommended trade studies are identified in Exhibit 5-10.

POLICY ISSUES

Policy issues on development of the Space Station for microgravity research and commercial activities are likely to be significant and could arise in several areas: pricing, schedules, research vs. production, propietary protection, public vs. private ownership, and international participation.

Industrial use will be a critical element in the success of the Space Station program. Industry involvement will be essential to achieving and maintaining a competitve position in the world market. At present, however, there is no pricing policy for the use of Space Station facilities or services. Thus, prospective users have no way of performing an economic analysis to determine the feasibility of Space Station ventures.

A pricing policy must be developed that will encourage industrial use of the Space Station. It is suggested that such a policy be based on the "national laboratory" concept; that is, the facility would be considered a national resource. It would be built and paid for by taxpayer money for the benefit of any qualified user. User fees for research would be sufficient to discourage frivolous use of the facilities, but would also be commensurate with risks and potential benefits. It may be advisable to have a variable user charge that would depend on the degree of proprietary protection the user desires. For research to be reported openly, the user charge should be

EXHIBIT 5-10
RECOMMENDED TECHNOLOGY TRADE STUDIES

EVA vs. robotics

Real-time interactive science (man) vs. telescience (machine)

Keeping quiet lab on station vs. branching to a platform -- vibration isolation

Advantages of alternate venting systems vs. storage and return (post operational disposal)

Training vs. selection of "best" people astronauts

Type of power for 1 mw -- nuclear vs. solar, tethering vs. microwaving, etc.

Decommission of microgravity and life sciences facilities or decontamination

Growth propulsion studies

Tethered lab for materials science investigations in the upper atmosphere

Permanent manned vs. man-visited microgravity and life science laboratories

Development of man-rated centrifuge

considerably less than actual cost. This would also help build the data base and encourage other users. For proprietary research or production, the user charge should be increased to cover actual operating costs. (However, the costs would have to be held low enough to make commercial operation viable.)

The most significant barrier to commercial space processing at the present is the high cost of transportation to low Earth orbit (LEO). Even at $80 million per Shuttle launch, it will cost $10,000 per kilogram to deliver raw material to the station via the logistics module. Very few (if any) products will be able to absorb this transportation cost -- plus user charges for processing on the station -- and still be sold at a profit. If there is to be any commercial production in space, vastly cheaper transportation must become available. A reasonable target should be $100 to $200 per kilogram to LEO. If research on the Space Station develops processes or products that are vastly superior to Earth-produced counterparts, there should be sufficient incentive for private development of very low cost cargo vehicles to deliver materials to and from the station.

Users must have regularly scheduled, reliable access to the Space Station. Time from experiment conception to implementation must be minimal. Commercial users must be given guarantees for delivery of specific resources and services they depend on.

The primary function of the Space Station laboratory modules will be to support basic and applied research and limited production or pilot manufacturing operations. The national policy must address the distribution of resources among activities to prevent a single user or a small group of users from monopolizing the available resources. The pricing policy must also provide for the transition of production operations to other Space Station elements (such as man-operated free-flyers) when resources requirements begin to interfere with other users.

Certain commercial research and production activities carried out on the Space Station will produce proprietary information. Steps must be taken to protect such information by limiting access. Companies should be allowed either to supply a payload specialist to perform the research or to execute legally binding nondisclosure statements with parties requiring access.

NASA should actively support and include in the planning of the Space Station commercially financed and developed elements that could replace or provide additional capability to the basic station. The Space Industries' industrial space facility is a specific example.

NASA must not, however, allow a critical element of the station or a facility needed by a variety of users to be developed as a commercial venture unless:

- There is adequate assurance that the company has the capability, the will, and the resources to complete the development
- A fair use and pricing policy for the investor-supplied components is in place.

International participation in basic scientific research and sharing of resources and equipment should be encouraged. Issues that must be resolved include cost sharing, resource allocation, pricing policy and user charges, liability/insurance, duplication of facilities, use of facilities, protection of sensitive or proprietary data, international crews, and technology transfer.

RECOMMENDATIONS

The growth and evolution of the Space Station microgravity research and commercial applications are predicated on two factors: strong industrial support for processing materials in space and the perceived need for man to operate for long periods of time in reduced gravity. To develop industrial support, several things must happen:

- NASA must establish a science base in microgravity processing that is relevant to industrial needs. Activities may include efforts to demonstrate that new or vastly improved materials of technological interest can be produced in space.

- A dependable, low-cost launch capability to LEO must be developed. Very few, if any, viable commercial efforts will be undertaken at the present launch costs (approximately $10,000 per kilogram). A reasonable target would be $200 per kilogram.

- NASA must establish policies on pricing and scheduling for use of station services and facilities and on protection of proprietary data. These policies will provide essential information so that prospective commercial users can perform cost/benefit analysis. The pricing policy should be similar to that used for national laboratory facilities (i.e., no attempt should be made to recover the cost of the facility or, in some cases, even the actual operating cost).

Assuming that these conditions are met, the core station can grow to meet the needs of a robust microgravity program for 5 to 10 years after IOC, depending on how rapidly other activities on the station are developed. To provide the resources to accommodate this growth, it is recommended that the power system be scarred to handle up to 300 kW across the gimbals and that the individual modules be scarred to handle power and heat dissipation up to 60 kW.

Growth on the core facility can proceed by adding new modules along the flight path to stay within the prime microgravity envelope. In addition, as many as four isolation/hazardous operations modules will need to be attached to the nodes to accommodate large superconducting magnets, centrifuges, and hazardous operations (such as large, high-pressure crystal growth facilities and biological quarantine). Servicing will also be required for man-operated, free-flying facilities (such as the man-rated variable-gravity facility and high-powered materials production facilities). Servicing will also be needed for automated or remotely operated free-flyers (such as the nano-gravity facility or the space ultravacuum research facility).

Several factors will dictate the time needed to evolve a separate Space Station (perhaps dedicated to microgravity operations). These factors are total power available, the ability to provide a suitable microgravity environment, and the basic incompatibility of requirements between the various activities on the core station. As the station grows, it will become more difficult to maintain the center of mass near the modules.

The microgravity team recommends an evolutionary path that will eventually lead to a "quiet" station dedicated to microgravity research. Such a station can use components of the core station, such as the modules, the "horizontal" truss, and solar dynamic power units, but will dispense with the dual keel and associated truss structure. Thus, only one new element, the horizontal truss, will need to be brought to orbit. The other components, such as modules and power units, will simply be added to the new station rather than to the core station. Growth concepts for the quiet station are shown on Exhibit 5-11.

The quiet microgravity station will co-orbit with the core station. It will be man operated but not inhabited. The crew will live on the core station. They will commute to the quiet lab for work using the OMV with a logistic or other pressurized module to avoid extravehicular activity. Since docking will be in line with the flight path of the center of mass, shifts in the gravity gradient accelerations can be avoided. Resupply requirements to the quiet station will also be minimized, as only materials to be processed will be brought to this station with the crew. Materials will be prepared and characterized on the core station to minimize disturbances on the quiet station. Eventually, as robotics and automation progress, manned operations on the quiet station can be expected to diminish.

The team believes that this approach will best satisfy all users for the foreseeable future. It will also ensure significant advances in microgravity-related disciplines and lead to commercially viable space industries.

CONCLUSIONS

Microgravity research and development can lead to a permanent industrial presence in space. It can also help us understand the productivity of humans during extended periods in space. Investigations of microgravity processing will be driven by research goals at first; industrial expansion will result when there is sufficient scientific understanding to produce profitable results. Life science investigations will be driven by a desire to improve crew performance, to understand the biological effects of extended space missions, and to gain a better understanding of the fundamental behavior of living systems ranging in scale from the cellular level to humans.

EXHIBIT 5-11
GROWTH CONCEPTS

ADDITIONAL MODULES FOR CORE (OR QUIET) STATION

- Isolation/Hazardous Operations Facilities
  - Logistic or short S/L module
  - Attached with airlock to nodes (four required)
  - Separate ECLS system
  - Applications for hazardous materials processes, super-conducting magnets, quarantine function on animals/samples, 4m centrifuge
- Dedicated Human Biomedical Research Facility
  - Develop effective low-g countermeasures
  - Evaluate/establish pharmaco dynamics
  - Develop long-term health maintenance requirements
  - Crew intensive
- Dedicated CELSS Module
  - Requires full-control, closed module
  - Attached payload test-bed
  - Free-fly platform control
- Dedicated Biological Research Facility
  - Crew intensive
  - Long-duration microgravity, seed-to-seed
  - 1.8m and 4.0m centrifuges
- Product Return Facility
  - Quick return (more frequent than 90 days)
  - Interactive experiments/product evaluation
  - Load from station node

UNMANNED FREE-FLYERS SERVICES FROM STATION

- Nano-g Research Facility
  - Use gravity probe B technology
  - Super-conducting liquid helium
- Space Ultravacuum Research Facility (SURF)
  - Man-tended free-flying wake shield
  - OMV deploy/retrieval
  - Service from airlock/berthing port

EXHIBIT 5-11
(CONTINUED)

MAN-OPERATED/TENDED FREE-FLYERS

- Dedicated Variable Gravity Research Facility
  - Long-duration capability
  - Gravity range from micro-g to 1 g
  - Possible tethered rotators
- Dedicated Microgravity Laboratory (Quiet Lab)
  - Lab modules and power system (150 kW)
  - Co-orbit with core station
  - Manned OMV bus between lab and core station
- Strategic Materials Production Facility
  - Man-tended free-flyer
  - 100 kW to 1,000 kW SP100-class nuclear reactor
  - Use standard lab module/outfit from airlock
- Quarantine/Analysis Facility
  - OMV deploy/retrieval
  - Man-tended
  - High A&R candidate
  - Capable of "sterilization"
- Industrial Production Facilities
  - Commercially owned/operated
  - High power
  - Man-tended

There is also a need to close the environmental control and life support system and to prepare for manned exploration of the Moon and Mars.

Most space-based life sciences research will continue to be performed on the initial manned core Space Station. Research will include microbiology, plant, animal, and human subjects. Growth will be through the addition of pressurized modules, including a plant and animal vivarium and a closed ecological life support system in a separate module. Later growth will involve pressurized free-flying modules for man-rated variable-gravity studies and for bioisolation. The bioisolation modules will provide added risk protection and could be used to quarantine martian samples. Additional unmanned life sciences free-flyers will include spacecraft for instruments dedicated to the search for extraterrestrial intelligence and to polar platform experiments on radiation effects.

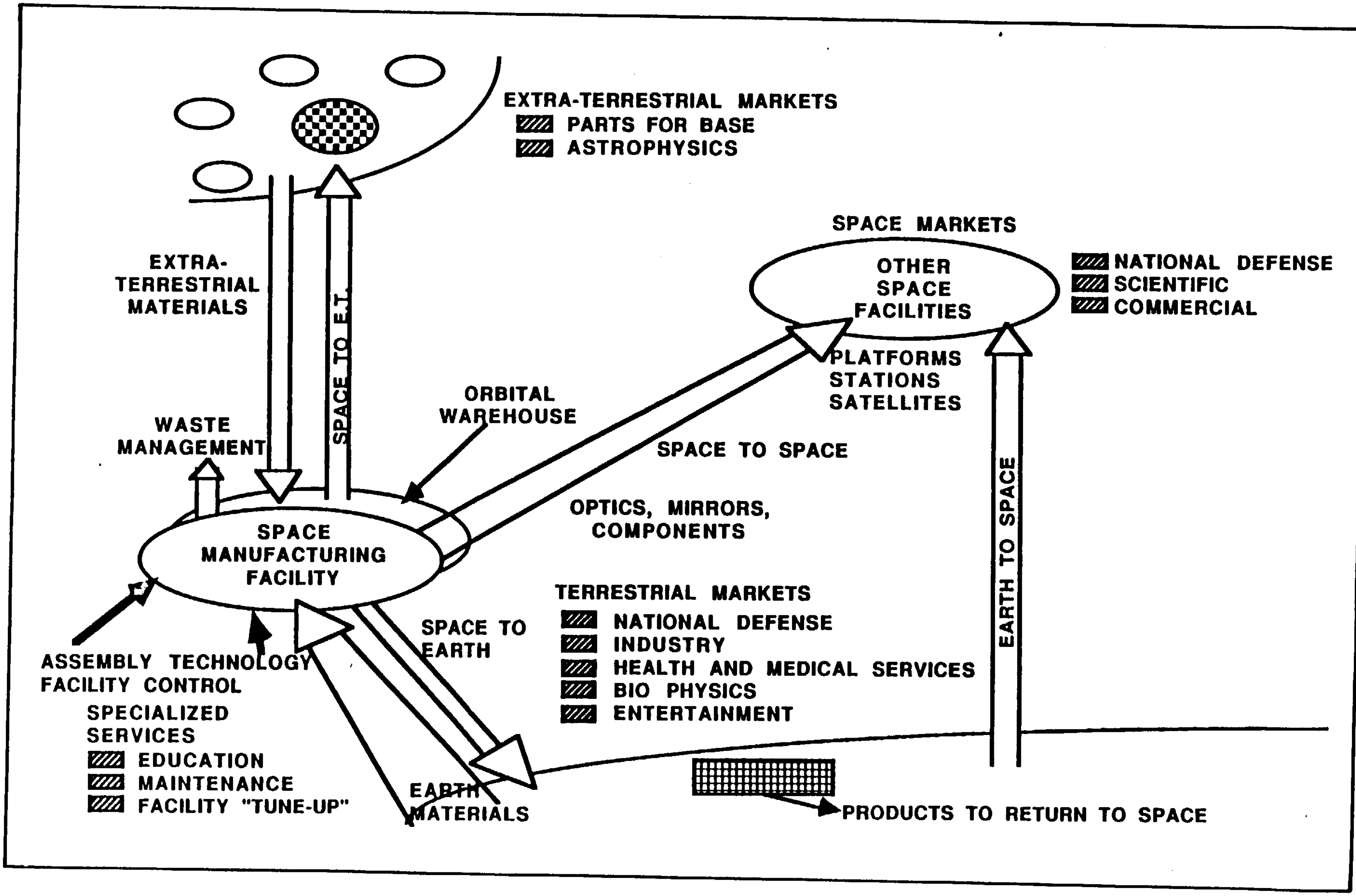
Early experiments in the materials laboratory module are likely to increase the demand for resources. Additional lab modules will be required on the initial Space Station, as well as separate free-flyers, both manned and unmanned. Several branch points are possible. After the research and development phase, certain production processes might be moved out of the laboratory onto automated, unpressurized, attached modules. These modules may be serviced and maintained by a mobile servicing carrier, or material and equipment could be passed through an airlock for intravehicular activity servicing.

Branching is a means of resolving the incompatibility between the microgravity users and other users of the Space Station. As industrial materials processing matures, production factories will be designed for specific processes and placed in orbits accessible from the Space Station for manned servicing. By this time, industrial parks will have been developed. The Space Station crew will commute to production and research facilities, where they will work inside pressurized modules or use manipulators for maintenance and repair.

In the long term, it is reasonable to anticipate space processing of extraterrestrial materials as well as Earth-provided materials. The application might include support of deep-space missions, manned Mars missions, lunar base construction, large commercial satellites, and national defense satellites, as shown in Exhibit 5-12. Such operations can be supported within the framework outlined in this study.

This scenario for the evolution of industrial space-based materials processing is only possible with an adequate transportation and support infrastructure. There must be sufficient access to a laboratory environment and dependable, routine transportation at an affordable cost. Given the current infrastructure, growth will be much more modest, with an expansion from one laboratory at IOC to perhaps two or three after a few years. For adequate transportation, a "space express" concept must be realized. Customers must be confident that they can get their payloads to orbit quickly and on a reliable schedule. A reliable, routine schedule for return to Earth is just as essential. In addition, the costs of such transportation must be reduced by more than an order of magnitude. Once these objectives have been realized, the commercial sector will invest in the expansion of the Space Station, factories, and transportation system to meet market demand -- independent of the rate at which the government expends its resources.

EXHIBIT 5-12
SPACE MANUFACTURING FACILITY EVOLUTION



6. EVOLUTION CONCEPT SYNTHESIS

6. EVOLUTION CONCEPT SYNTHESIS TEAM REPORT

The objectives of the concept synthesis team were:

- To synthesize discipline team concepts and requirements into options for evolution of the Space Station Program infrastructure

- To recommend changes to the initial operating capability (IOC) Space Station and to identify important growth areas for Space Station planning

- To compile lists of recommended studies and analyses to provide a deeper look into aspects of the Space Station program evolution options.

The workshop teams' recommendations on features to be included in the initial Space Station configuration point the way toward evolution paths that otherwise would be difficult to achieve. The teams recommended many current concepts that should be retained because they are important to evolution planning. They also recommended new concepts that should be considered because they may open other evolution possibilities or because they would be difficult to incorporate later.

The starting point for the development of each evolution program option was the 1995 initial configuration Space Station. This configuration was assumed to have five basic components:

- Core Space Station. The permanently manned core Space Station will have a microgravity lab; a life sciences lab; Earth, solar, and stellar viewing capability through externally mounted instruments; and an initial satellite-servicing capability.

- Polar Platforms. Unmanned polar platforms will be launched from the Western Test Range at Vandenberg Air Force Base either by the Shuttle or by an expendible launch vehicle (ELV). They will be serviced by the Shuttle or by an orbital maneuvering vehicle (OMV).

- Co-Orbiting Platforms. Unmanned co-orbiting platforms will be launched from the Eastern Test Range at Kennedy Space Center either by the Shuttle or by an ELV. They will be serviced from the core Space Station by an OMV.

- Orbital Maneuvering Vehicles. OMVs are versatile intra-orbit tugs that can be based and serviced on the ground or on the Space Station.

- Ground-Based Support Facilities. The infrastructure will include the Eastern and Western Test Ranges, the TDRSS data/communication network, and control centers.

The concept synthesis team took as a given that the Space Station and the transportation systems must evolve together in an integrated fashion. Thus, requirements for new transportation capability are included as part of the Space Station options described later in this section.

In developing the evolution path options, the team also assumed that the Space Station evolution will be user driven. No attempt was made to impose budget, transportation, or political realities on the options. Such constraints should be the subject of future analyses.

MISSION REQUIREMENTS

The requirements identified by each discipline team are shown on Exhibit 6-1. This summary includes only the top-level requirements expected to drive Space Station program evolution or to affect other discipline requirements and implementations.

Conflicts between the requirements of the five disciplines are apparent. Lunar and planetary exploration, for example, will involve frequent arrival and departure of OMVs, OTVs, and cargo and transfer of material from the core station to platforms and other vehicles. The result of this activity will be disruption of the microgravity level.

Microgravity research may require a more stable microgravity environment than the multipurpose core station can provide. The need for a "quiet" research laboratory thus will drive the evolution to separate research and transportation facilities. The conflicts between the requirements of lunar/planetary exploration and the requirements of astrophysics and Earth observation activities are similar. These disciplines will require minimum contamination and unobstructed views of the Earth and the stellar system.

INFRASTRUCTURE EVOLUTION OPTIONS

The concept synthesis team developed three options for Space Station evolution: the broad capability development option, the commercial production encouragement option, and the lunar and planetary initiative option. In addition, the effects on evolution of a severely limited transportation system were assessed for comparison. The options are discussed in the sections that follow.

EXHIBIT 6-1
MISSION REQUIREMENTS

Astronomy and Astrophysics

- Servicing and upgrading of modular free-flying platforms
- Basing and servicing for small attached and free-flying instruments
- Capability for assembly, operation, and deployment of new large-scale facilities supporting astrophysics research
- Low cost Earth-to-orbit transportation
- Early cryogenics and refueling logistics capability
- "Shirt sleeve" hangar for servicing large systems
- Facilities and capability for cleaning and recoating optical surfaces on-orbit (desirable in the short run, required in the long run).

Communications

- Assembly and deployment of large structures
- Space-Station-based servicing and storage bay
- LEO servicing, check-out, and repair for both scheduled and unscheduled events
- GEO servicing and upgrading for scheduled events
- Space-Station-based test facility for large antennas and spacecraft
- Low-cost transportation to LEO
- Low-cost space-based orbit maneuvering capability
- Low-cost, low-thrust (0.1 g) space-based orbit transfer capability
- NASA support for R&D on large antennas and spacecraft structures
- An OTV able to carry and service multiple spacecraft

EXHIBIT 6-1
(CONTINUED)

- Teleoperator and robotic capability

- Early capability for extravehicular activity (EVA) (over the long-term, automation will diminish the need for EVA capability).

Earth Observing Systems

- Polar platforms for maintaining global coverage and constant sun angle and for performing diurnal variation studies

- GEO platform

- Manned element of the core Space Station with:

  - A plasma physics laboratory

  - Accommodation for attached instruments and instrument development

  - Accommodation for large structures

  - Burst-energy storage facility

  - Contamination control capability

- Platform-servicing capability

- Low-gravity OTV for delivery to GEO

- Robotic servicing capability for GEO platforms.

Lunar/Planetary

- Advanced Earth-to-orbit transportation providing increased lift and greater frequency at a lower cost

- Facilities in the core Space Station for:

  - Long-duration studies of low-gravity effects
  - Cryogenic fluid handling and storage
  - Closed-loop environmental control and life-support
  - Quarantine
  - Logistics and servicing
  - Assembly, operations, and training
  - Agricultural research

- Evolution Space Station support to the Mars mission to provide:

  - Attachment space and functional interfaces and resources

EXHIBIT 6-1
(CONTINUED)

- Assembly and check-out for systems and crew
- Propellant tanking
- Maintenance, refurbishment, and storage of lunar and planetary mission systems
- Retrieval of returned planetary mission systems by a space-based OTV
- Quarantine facilities for returning crews and materials
- Nuclear reactor power generator handling and facilities.

<u>Microgravity</u>

. High power
. Extensive crew participation
. Low-cost, dependable transportation to orbit
. Research facilities, including:
    - Dedicated microgravity laboratory
    - Strategic materials production facility
    - Nano-gravity research facility
    - Space ultravacuum research facility
    - Isolation and hazardous operations facility
    - Human biomedical research facility
    - Variable-gravity research facility
    - Quarantine and analysis facility
    - Closed-loop environmental life support system module
    - Logistic module access
. Rapid sample return capability.

Option 1: Broad Capability Development Option

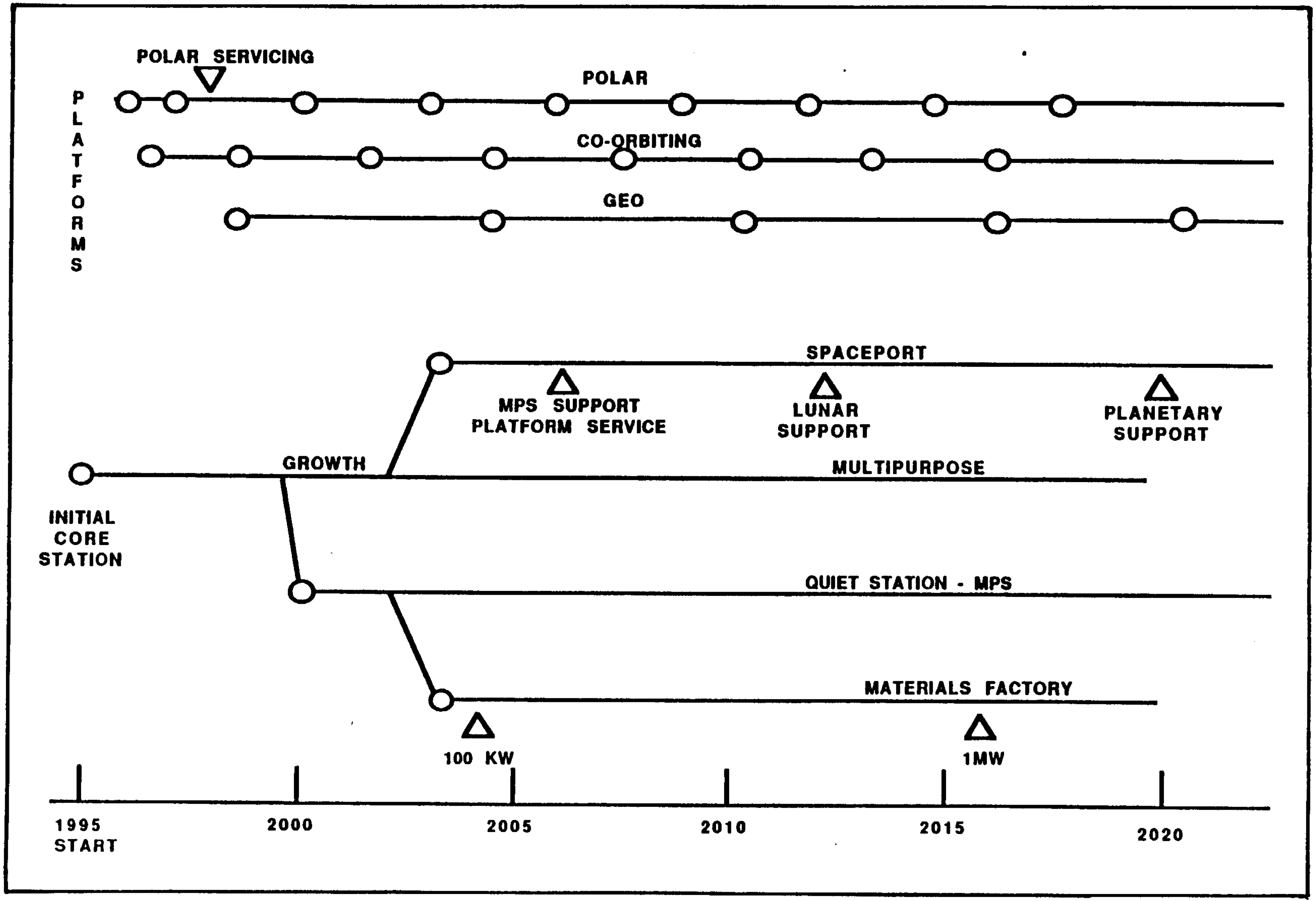
The broad capability development option is an aggressive evolution path that is responsive to the requirements developed by each of the discipline teams. This scenario involves three branching paths for the core station and continued incremental evolution of the platforms, as illustrated in Exhibit 6-2.

The first core station branch will be constructed to support continued microgravity research 5 to 10 years after initial station operations. The impetus for this branch point will be the need for stable microgravity levels as expanded core station use increases the level of disturbances. The microgravity station -- the quiet station -- will provide a facility for research and development to meet commercial/DOD microgravity needs as well as the requirements for basic research. Certain types of microgravity life science research could also be accommodated in this station if they do not disrupt the microgravity environment.

Crew support will be required, but continual habitation would disrupt the microgravity environment. Ideally, the microgravity station would be close enough to the original station to allow crews to commute to and from the branched station at regular intervals. Physically, the station might consist of a single truss supporting power plants and laboratory modules. Like other infrastructure discussed in this report, the facility may be budgeted and constructed by the government or by private industry.

This branch point will form the basis for a second branching: additional free-flying facilities for the start of a new materials production industry. This branching from the quiet station will occur 10 to 15 years after IOC. Initially, the materials factory will require about 100 kW of electrical

EXHIBIT 6-2
BROAD CAPABILITY DEVELOPMENT OPTION



power, increasing to about 1 MW over 5 to 10 years. Eventually, facilities to generate nuclear power or another type of power will be needed.

The third branch from the initial core station will provide a transportation node capability. It will initially serve the transportation needs of the microgravity community and will evolve to support the lunar sortie missions, lunar base missions, Mars sortie missions, and manned Mars missions. The continued use of this transportation node by the microgravity community will depend on the practicality of time-phased sharing with the lunar and planetary community.

The initial station will continue to evolve in support of multipurpose operations, including astronomy and astrophysics, communications, and Earth observations. Most servicing operations and large-space construction will move from the multipurpose station to the spaceport when it is developed. Larger structures will require servicing 5 years after station activation. The servicing function will grow as the frequency of servicing operations increases, more types of propellants and cyrogenic fluids are handled, servicing becomes more complex, and servicing tasks are added as technology advances make optics refurbishment and other advanced tasks practical. In situ servicing requirements will also increase as geosynchronous (GEO), polar, and co-orbiting platforms are added. Very large structure assembly (200 meters by 200 meters) will be required about 10 years after the initial station activation. At this time, data and communication requirements will also increase to a level of 1 giga bit per second.

Although branching provides the capability to support two major space thrusts independently (microgravity research and development (R&D) and lunar/planetary exploration), the requirements for initial station capacity will be reduced by only a small amount. The relocation of microgravity work to a branched station will reduce somewhat the requirements for power, crew EVA time, and pressurized volume resources, but growth in other station activities will probably restrict these savings to power only. However, the remaining assets can be used more efficiently as less time-sharing by conflicting activities is required. The transportation node station will reduce requirements for crew time on the initial station and provide for more homogeneous crew activities.

Transportation capability evolution is a constraint on evolution to these branch points. The supportive transportation evolution is defined in Exhibit 6-3. Although all the capabilities shown are required for the broad capability development scenario, the key to achieving both branch points is increasing the Earth-to-LEO and return-to- Earth capability. This capability increase will be required 5 to 10 years after station activation to support an annual transportation capacity of 350 metric tons, in both "up" and "down" modes, primarily of microgravity materials. If this requirement is satisfied by a heavy lift expendable vehicle, other provisions must be made for the down weight. The lunar and Mars missions will intensify this growing requirement during the next 5-to-10-year period, although the down weight requirement will be considerably reduced. Other supporting transportation elements include OMVs, OTVs, manned OMVs, a lunar lander, and a Mars lander.

Other constraints on evolution include data, communication, and tracking capabilities. The Mars mission will require rebuilding (probably space based) the deep-space network. The addition of more low Earth orbit (LEO) and new GEO Earth observation platforms, plus the requirement for correlated observations from different platforms, will call for continual

EXHIBIT 6-3
SUPPORTING TRANSPORTATION EVOLUTION

INITIAL CONFIGURATION

STS
OMV
ELV'S

5-10 YEARS

ADDITIONAL MANNED TRANSPORT
MANNED OMV
LOW THRUST OTV (0.1.G)
350 TONNES/YR

10-20 YEARS

EVOLVED OTV
HLV
LUNAR LANDER

15-20 YEARS

MARS TRANSFER VEHICLE
MARS LANDER

increases in data collection, storage, and dissemination capability and additional capability to provide unified platform control.

Platform evolution involves increasing numbers of platforms, including the addition of non-sunsynchronous, high-inclination platforms and GEO platforms for Earth observation.

Option 2: Commercial Production Encouragement Option

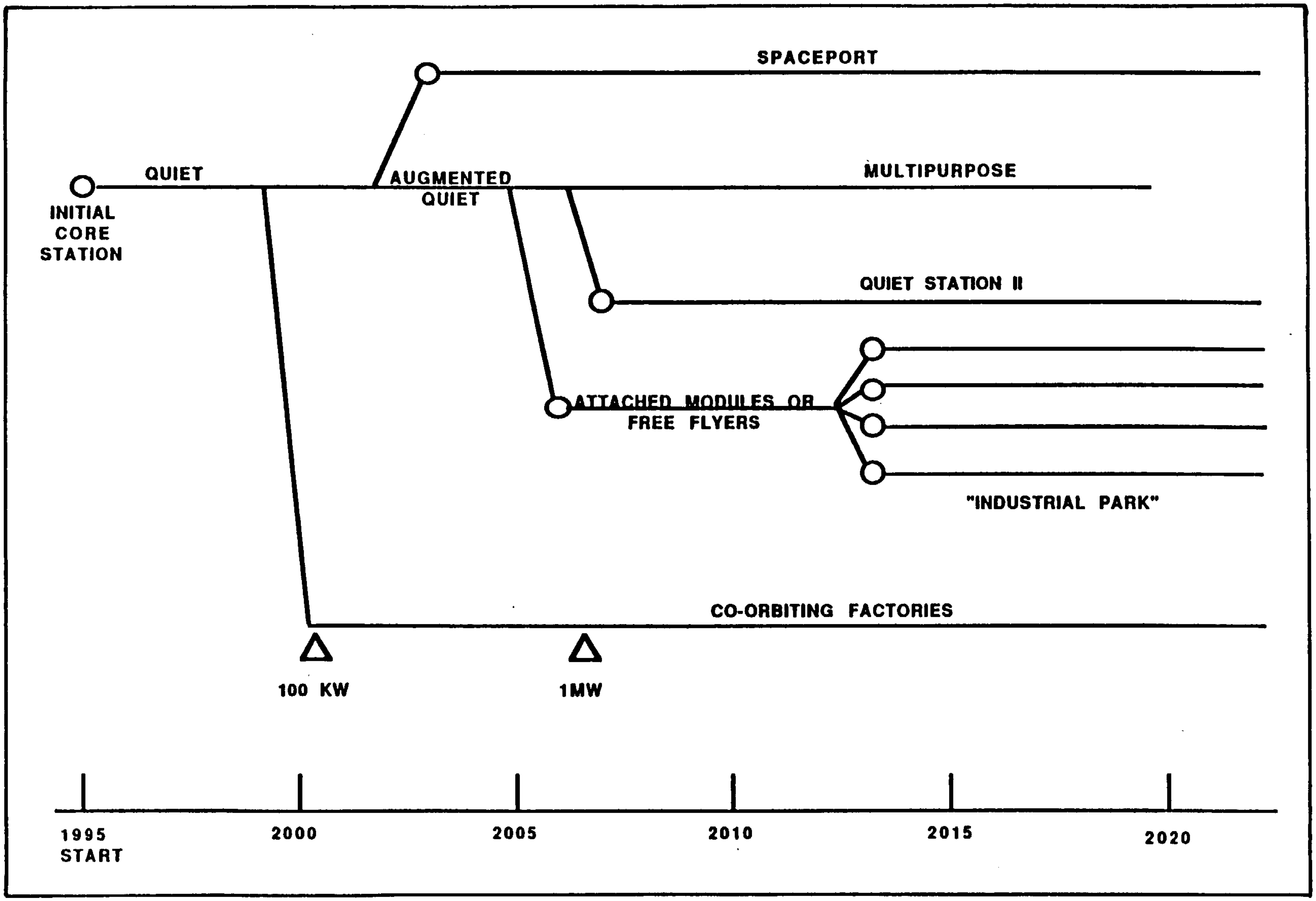
Under this option, policies will be established to encourage commercial initiatives in space. This option could open up opportunities for private industry in:

- Earth-to-orbit transportation
- Element-to-element (in-space) transportation
- Materials production
- Production facility development:
  - Build and sell
  - Build and lease
- Space utilities and services.

The emphasis under this option will be on developing "quiet" (steady-state microgravity), secure, high-power facilities. As shown in Exhibit 6-4, such facilities will be initiated on the IOC manned core by 1995 and will be shared between the disciplines. However, microgravity research will have precedence over other disciplines.

Commercial experimentation on the core station will be conducted to develop materials and processes in the newly available environment. Such R&D efforts are likely to lead to promising new products for pilot production plants on the core station. R&D will also be undertaken to demonstrate the capability to produce commercial sizes and quantities of materials and to determine the marketability of the products.

EXHIBIT 6-4
COMMERCIAL PRODUCTION ENCOURAGEMENT OPTION



Once the viability of commercial production has been shown, the next step will be to move into co-orbiting factories dedicated to specific commercial enterprises. At the same time, the initial manned core will be updated for further experimentation in the commercial arena and for basic scientific research.

Some 10 to 15 years after the initial capability, a second-generation microgravity Space Station will be required. With the introduction of this "Quiet Station II," the original station will revert to the multipurpose support originally envisioned.

Additional factories will be needed at this time as well. These facilities may be provided by the industry doing the production or by commercial entrepreneurs. The factories may be modules attached to the quiet station or free-flying facilities. The attached modules will be for production that does not require very low gravity, such as pharmaceuticals; the free-flyers will be used for activities that require long periods of very low gravity, such as crystal growth. The factories will be automated, but man operated. The crews living on the nonquiet core station will be transported infrequently to the facilities to perform maintenance and service, to resupply consumables, and to retrieve produced items.

It is difficult to predict the growth of commercial production; however, estimates indicate that 5 to 10 years after initial operation, there will be requirements to transport as much as 300 to 400 tons of material to orbit and return. This magnitude of resupply and return should encourage the participation of commercial transportation enterprises. In addition, another branch to a transportation node will be required to handle storage, docking, and unloading/loading of Earth-to-orbit vehicles without adversely affecting the environment of the multipurpose station. In-space transportation, such as a manned OMV, will then be used to carry crews to the factories.

At 15 to 20 years after IOC, clusters of factories from different countries may be sufficient to form a kind of industrial park in space. Such an industrial park would eventually be much like a ground-based industrial park, with a developer initiating the basic space allotments. The park would include:

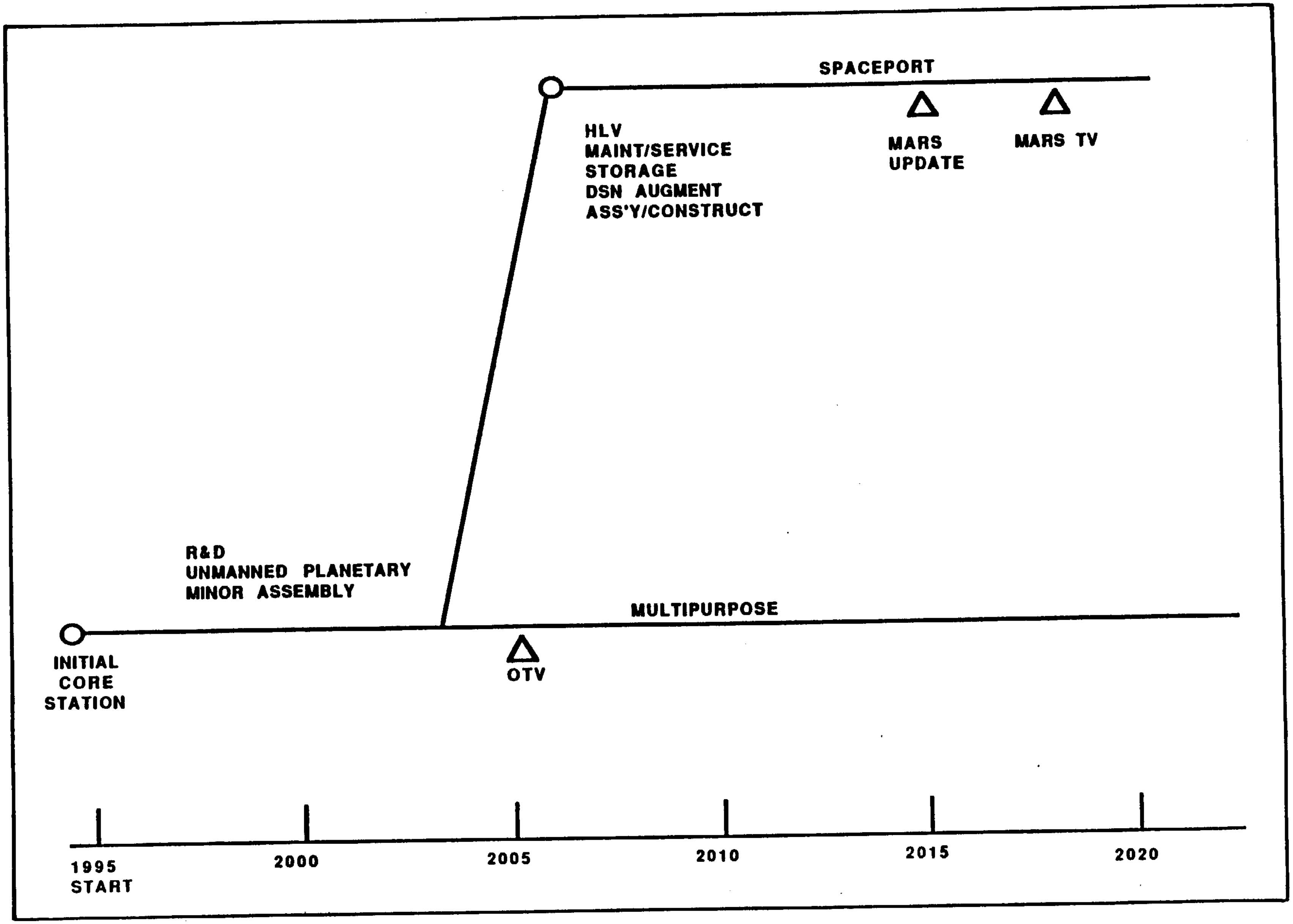
- A power company module
- A trash collection agency (waste/management)
- "Trucking" company(s) for resupply
- A ground-based supply/distribution complex
- A maintenance crew and shop areas for repair
- A space facility production industry.

Option 3: Lunar and Planetary Initiative Option

This option assumes that the recommendations of the National Commission on Space (NCOS) for achieving a manned presence on the Moon and/or Mars will be adopted. It also assumes that this initiative will become the top priority for the Space Station. The resulting evolution scenario is shown in Exhibit 6-5.

Under this option, Space Station evolution will proceed following an integrated concept for a lunar/planetary initiative. This concept consists of four elements -- element 1, R&D activities; element 2, unmanned planetary missions;, element 3, manned lunar sorties/base; and element 4, manned Mars missions. The first two elements are basically compatible with a multipurpose Space Station.

EXHIBIT 6-5
LUNAR AND PLANETARY INITIATIVE OPTION



In element 1, the R&D activities include research to understand the effects of long-duration micro-gravity and partial-gravity (1/3 g and 1/6 g) conditions on crew capability; crew performance in isolated environments; agriculture for long-duration missions; and long-duration performance of equipment (particularly for the Mars mission). These activities will be conducted as part of the life science, crew physiology, and technology programs on the station. They will require only minor additional support.

The unmanned planetary launch activities of element 2 will begin at IOC and continue at a rate of slightly less than one per year. These will initially involve mating of upper stages and spacecraft checkout and launch. Once the OTV becomes available, it will be used in a recoverable mode for these launches. Capability will be required at the Space Station for protective storage, vehicle assembly, and some operations (such as orbital altitude adjustment). Because of the small impact on other station functions, this phase is assumed to be compatible with a multipurpose station.

The element 3 lunar sorties will begin in 2005, and a lunar base will be established by 2010. Supporting activities will be heavy operations, causing disturbances and potential for contamination from fuel spills and ventings. Thus, a spaceport will be required at this time. One lunar round trip will be made every 55 days. The lunar base crew, consisting of 10 to 30 members, will require extra housing during crew rotation. The spaceport in this case may be co-orbiting with the initial Space Station. Thus, some resources could be shared (e.g., the spaceport could provide housing for the Space Station crew or vice versa).

In element 4, the first manned Mars mission will be launched in 2015 and, given an ambitious program, could be followed by additional launches every 26 months. Interplanetary transportation services will be required to support permanently manned facilities on Mars. The major construction/assembly associated with this mission will also require a spaceport. The existing lunar spaceport could be augmented to support the Mars missions, or a second spaceport could be established. If a single spaceport is constructed to support both lunar and planetary operations, two vehicle assembly piers will be needed.

Under this option, it is assumed that some modest growth of the initial station will occur to support other user communities. This growth will occur between transportation availabilities. The resulting capability for the initial station would be 150 kW of power, a crew of 12, support for four labs, and support for one OTV.

Elements 1 and 2 can be accomplished by the IOC Space Station with relatively little interference to other activities. From 60 to 80 percent of element 1 will be identical to missions already in the mission data base; the main differences will be increased emphasis on long-duration human and hardware performance.

The evolution break point will occur when the decision is made to proceed with manned lunar or planetary missions. Decisions on Space Station evolution to support these missions can be taken at that time.

Activities to support manned lunar and Mars missions will begin to make significant in-roads on the availability of Space Station services for other users. One lunar mission will dominate major operations for 2 to 4 months (2 months will be adequate for routine operations, but initial missions will be assembled and checked out more meticulously over longer periods). A manned Mars mission would take over the Space Station for about a year.

Under such a scenario, the Space Station will be used full-time as a spaceport. Vehicle arrivals and departures will occur weekly or perhaps more often, and the center of gravity of the Space Station will be continually disrupted. The spaceport will be essential at this point to preserve other uses of the core station.

Several constraints are associated with this option. The most significant is the problem of Earth-to-LEO transportation. Lunar base support will require one round trip every 55 days, or the equivalent of 36 Shuttle flights per year. Clearly, an advanced transportation system will be required for this mission. A heavy lift launch vehicle will probably be the choice. Support for the manned Mars mission will require the equivalent of 40 Shuttle flights per year. Some elements to be transported are large (the aerobrakes) or massive (propulsive stages). Again, a heavy lift launch vehicle will be required.

Another constraint may be the need for storage and reliquification of cryogenic propellants in large quantities (in the order of 100,000 kilograms for the lunar base missions). Technology development in this area will be required.

A third constraint is the unique requirement in planetary launches for orbital plane alignment with the transfer trajectory plane. Thus, the orbital altitude of the Space Station may need to be controlled to allow proper nodal regression for alignment. The requirement may conflict with other station needs, including resupply. It may also preclude support of lunar base and manned Mars missions from the same Space Station. Further study will be required.

A fourth constraint involves the TDRSS and deep-space network, which, as currently planned, will be inadequate to support extensive lunar and planetary mission activities. Major augmentation will be required.

Safety may be another constraint. Manned lunar and planetary missions may use nuclear systems that must pass through the Space Station in LEO. The resulting policy and safety issues must be resolved. In addition, assembly, construction, and servicing activities for the manned mission will require extensive EVA and/or telerobotics, some of which will be hazardous.

Transportation-Limited Evolution

Because transportation is such a fundamental aspect of the Space Station program, it is important to consider the impact of possible constraints in this area. Limiting assumptions were made to scope the effects of severe transportation limits on various options. Disturbingly close to current estimates of transportation availability in the early to mid 1990s, these limiting assumptions are as follows:

- There will be 12 Shuttle missions per year.
- Payload to the 250-nmi core station orbit will be limited to about 36,000 pounds due to engine thrust limits and increases in vehicle weight to accommodate safety features.
- DOD will require six Shuttle missions per year for national security payloads.
- About four Shuttle missions per year will be available to the Space Station.

- Two Titan IV ELVs will provide additional support to the Space Station. Each Titan IV will be roughly equivalent to the Shuttle in its ability to transport payload to 250 nmi.

- Some form of material return capability will be developed to supply a down weight capacity of about 5,000 to 10,000 pounds per year.

- OMVs will be unmanned until 2000.

- Unmanned OTVs for GEO will be available in the late 1990s.

- Vandenberg AFB Shuttle operations will be postponed indefinitely.

- Shuttle II or an alternative will not be available before 2005.

- Heavy lift vehicles will be available after 2005.

- Crew sizes will be limited due to rescue considerations.

The impacts of these limitations will be extreme:

- Total payload weight to the Space Station will be limited to 200 to 250 thousand pounds per year.

- At four Shuttle flights per year to service the Space Station, supplemented by two Titan IV ELVs, IOC will be delayed and scaled down, and no growth will be feasible. At six to eight Shuttle flights per year, IOC may be delayed, but limited growth in both crew size and power will be possible.

- Branching will not be possible until after 2005, when additional transportation capability to LEO is realized.

CONCLUSIONS AND RECOMMENDATIONS

The Space Station configuration taken as a point of departure for this workshop will serve as an excellent platform to facilitate and support the exploration of space and space applications. Space Station plans should allow for growth in the following areas:

- Automation and robotics
- Construction of very large structures
- Storage area and volume
- Accommodation for expendable and reusable stages
- Data storage, processing, and transmission
- Closed-loop life support systems
- Facilities to support and service man-operated free-flyers
- Facilities for a spaceport.

It is further recommended that current concepts for the initial configuration be amended as follows:

- Increase the basic capability of the manned station to handle 300 kW electrical power
- Provide capability for radiation protection for extended crew stays of up to 2 years
- Retain the active berthing capability on all unused node parts
- Provide a second TDRSS antenna for data growth
- Restore the S-band capability to support housekeeping data
- Ensure that the initial Space Station design does not contribute to the orbital debris problem.

The workshop could provide only a quick-look study of evolution possibilities. Much effort is required to review the workshop results and to define details of the options. To examine further the issues and concerns that surfaced at the workshop, the studies and analyses shown on Exhibit 6-6 are recommended.

EXHIBIT 6-6
RECOMMENDED STUDIES AND ANALYSES

- Integration of transportation and Space Station evolution

- Realistic mission models for evolution

- Branching:

  - What are the technical drivers?

  - What functions should be branched?

  - Can technology developments delay the need for branching?

- Feasibility of man tending from the Space Station

  - Rendezvous opportunities
  - Manned transport between spacecraft
  - Dynamic effects on spacecraft

- Crew activities versus automation and robotics:

  - What is the optimum mix for the evolution time period?

  - What robotics capabilities must be developed?

- On-orbit repair and storage:

  - What level of repair should be provided?
  - What type of facilities should be provided?

- Location of OTV and propellant farm facilities

- Construction/assembly and deployment of large structures at the Space Station

  - What are the dynamic effects?
  - What facilities are needed?

- Variable-gravity facility:

  - Is it required and when?
  - Where and how should it be accommodated?

- Accommodations for advanced missions

  - Assembly/check-out, staging, refueling, and servicing of lunar/planetary missions

EXHIBIT 6-6
(CONTINUED)

  - Robotic servicing at GEO
  - Quarantine facilities or hazardous lab facilities
- Verification and testing for long-life autonomous operations
- Requirements for crew make-up and training
- Rapid sample return capability
- Servicing of high-inclination platforms
- Methods of cost reduction
- Commercial policy options:
  - How can commercial use of the Space Station be encouraged?
  - How can commercial provision of Space Station facilities, components, and operations be encouraged?
  - How can commercial policy be made consistent with international aspects of the program?

7. TECHNOLOGY SYNTHESIS

7. TECHNOLOGY SYNTHESIS

This year's evolution workshop departed somewhat from last year's in that the user community was given an opportunity to influence the technology synthesis report directly. This was accomplished both through the workshop organization and the assignment of technologists to the user teams. The participation of the technologists offered the users a view of available technology, the direction of future technology development, and the time frame of future availability.

Each user team discussed a wide variety of enabling and enhancing technologies. Using the discipline technology categories developed at last year's workshop, the teams then compiled a comprehensive catalog matching requirements and technologies. The original discipline technology categories are shown in Exhibit 7-1. As discussions within the user teams progressed, it became evident that the categories did not encompass the whole spectrum of user technology interests and desires. Therefore, four additional categories were added to the list. These included assembly, servicing (which includes maintenance requirements), facilities/modules/systems (which include technology requirements of the on-board Space Station), and contamination.

The goals of the technology synthesis team were to identify the highest priority for each of the user groups and then to define key enabling technologies across all user groups. Exhibit 7-2 shows the steps in this process.

The team began by collecting the user team requirements, which were then time-phased to the missions defined by each

EXHIBIT 7-1
TECHNOLOGY DISCIPLINES

Attitude Control System

Automation and Robotics

Communication and Telemetry

Data Management System

Extravehicular Activity (EVA)

Environmental Control/Life Support System (ECLSS)

Fluids

Manned Systems

Materials

Mechanisms

Power

Propulsion

Structures

Thermal

EXHIBIT 7-2
TECHNOLOGY SYNTHESIS TEAM METHODOLOGY

1. Collect requirements
2. Map evolution schedule
3. Develop technology discipline-mission team matrix
   - Add technology unique to individual team
   - Add "facility developments"
   - Experiment with TDMs/DEMOs
4. Extract, synthesize, and prioritize
   - Trends, recurrent techniques
   - Functional capability groups
   - General themes
   - IOC interfaces
5. Define
   - Key technology issues/tall poles
   - Discipline technology programs
6. Remap against concept synthesis

team. A matrix was created (as shown in Exhibit 7-3) that matched the discipline technology requirements shown in Exhibit 7-1 to the teams that defined the requirement. Each team was also asked to give its view of the technologies required for "experimentation," with particular emphasis on orbital mission demonstrations and technology development missions. The objective was to determine the extent to which Space Station-based and other flight testing formed an integral part of an evolutionary technology program.

In the next step of the process, the team extracted the major technology drivers from the overall set of requirements provided by each user team. To identify important themes, data were evaluated for trends, recurrent technologies, and groupings of functional capabilities. The results of this evaluation were then prioritized in order of importance for each user team.

The matrix in Exhibit 7-3, when completed with a comprehensive set of all team data, will produce a total "picture" for each discipline technology program. Once the enabling high-priority technologies for each user team are placed in such a matrix, the technology "tall poles" for that user team can be readily identified.

REQUIRED TECHNOLOGY

The technology synthesis team worked with the user teams to produce both the individual technology requirements/mission needs and the technology tall poles. The results of these deliberations are discussed for each of the user teams in the following paragraphs.

Astronomy and Astrophysics

Exhibit 7-4 shows the comprehensive set of mission/ technology requirements defined by the astronomy and

EXHIBIT 7-3
TECHNOLOGY REQUIREMENTS MATRIX

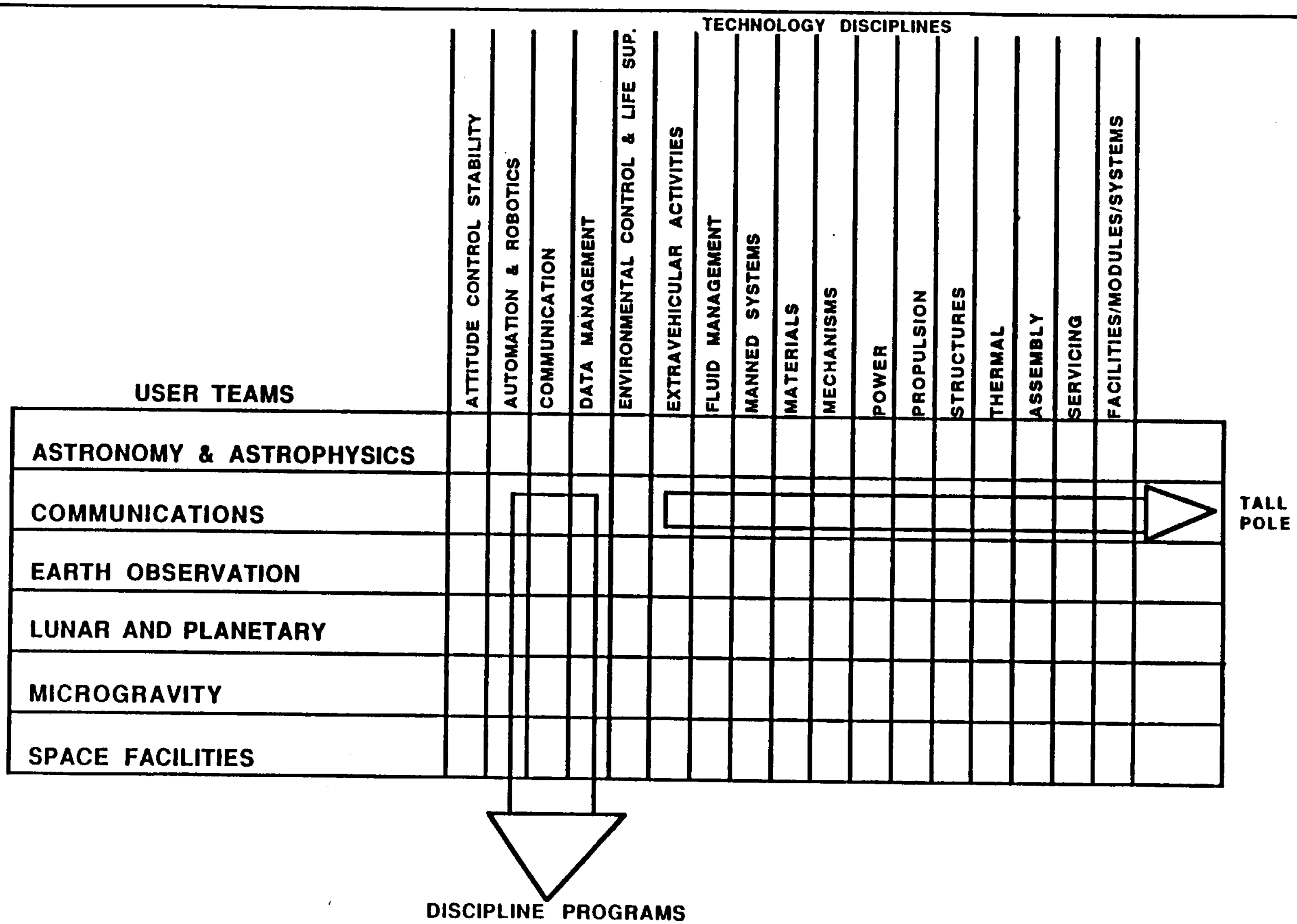


EXHIBIT 7-4
TECHNOLOGY REQUIREMENTS FOR ASTRONOMY AND ASTROPHYSICS MISSIONS

Area	Specifics	Missions	When
Guidance, Navigation & Control	Precise Navigation	VLBA; Adv. Pinhole Occultor	Near
	Attitude Knowledge	Adv. Optical Telescope	Near
	Attitude Control	Adv. Optical Telescope	Near
	Relative Alignment	Thinned Aperture Telescopes	Far
	Active Figure Control	Multi-Element Optics	Far
	Coarse Pointing System	Attached Telescopes (HRSO)	IOC
Automation & Robotics	Telerobotics	Servicing; Assembly	IOC
	Intelligent Robots	Servicing; Assembly	Far
	Ground Expert Systems	Monitoring; Planning	IOC
	Telescience	Solar; Others(?)	IOC
STR/Material	Precise Metering	Thinned Aperture Telescopes	Far
	Thermal Stability	Optical Telescopes	Near
	Non-contaminating	Optical/IR Telescopes	IOC
	Large Structures	Multi-Element Arrays	Far
	Large Workshop (Press.)	Various (Assy, Repair)	Far
Mechanisms	Active Figure Control	Multi-Element Telescopes	Far
	Pointing Systems	Telescopes	IOC
	Vibration Isolator	Attached Telescopes	IOC
Transport	To/From LEO	Place/Recover/Service	IOC
	To/From GEO	Place/Recover/Service	Far
	Man to GEO (?)	Coherent Optical Array	Far
Manufacture	Replicated Elements	Multi-Element Telescopes	Far
	Modularization	Multi-Element Telescopes	Near;Far
	Containerization	All (Launch Efficiency)	Near;Far
Environmental Control	Cleanliness	Optical/IR Telescopes	IOC
	Monitoring	Various	IOC
Servicing	Clean Optics	Optical/IR Telescopes	IOC
	Coat/Re-Coat Optics	Optical/IR Telescopes	Far
	Replace/Repair Modules	All (High-level Repair)	IOC
	In-Module Repair Bench	All (Low-level Repair)	Near
	Replenish Cryos (LHe)	IR Telescopes; Others	IOC;Near
	Propellant Re-supply	Facilities/Observatories	IOC;Near
	Calibration/Alignment	Various	IOC

Near - Within 5 to 10 years of IOC
Far - More than 5 to 10 years from IOC

astrophysics team. The data relate the missions to technology "specifics" for the eight identified technology areas. The exhibit also formats the missions into near, initial operating capability (IOC), and far time frames, as shown.

From the exhibit, it can be seen that the need for precision drives the technology requirements in the areas of attitude control, structures, and mechanisms. The needs for cleanliness, servicing, and automation are also important.

A more definitive set of technology issues for astronomy/ astrophysics is presented in Exhibit 7-5. There is a strong need to provide processes and facilities in space for completing the development and testing phases of missions in this field before they become operational. Because of their physical size and the need for precision, many of these missions cannot be launched completely assembled and integrated on the Shuttle. Thus, final integration and testing must be accomplished orbitally at the Space Station.

Once operational, these missions will look to the Space Station for in-space maintenance and repair, servicing, instrument changeout, and resupply. There will be particular emphasis on providing these capabilities in a contamination-free environment. Automation and robotics technologies were also seen as a necessity for providing orbital services in a timely, precise, and cost-effective manner. The team also stressed the importance of telescience to both operational and scientific mission objectives.

Communications

Key technology issues and tall poles identified for the communications team are shown in Exhibit 7-6. This team did not take a particularly aggressive technology posture. The industry

EXHIBIT 7-5
KEY ASTRONOMY AND ASTROPHYSICS ISSUES AND TALL POLES

Advanced Astrophysics Initiatives will require new processes and facilities for:

- On-orbit assembly of large precise structures
- Testing meterology and calibration in space
- Repair and resupply, including cyrogen replenishment
- Facilities for long-duration maintenance and refurbishment

Automation and robotics advances will provide major benefits in:

- Assembly and servicing
- Telescience for more effective operations

Technologies to reduce the cost of instrument development, fabrication, and delivery are crucial for:

- Modular design and containerized launch
- Advanced transportation aspects (OMV, OTV, Low-thrust OTV)
- Potential benefits of on-orbit manufacturing

Large pressurized workspace may be essential to:

- Improve crew efficiency and effectiveness
- Enhance additional processes/operations

Contamination is a recurrent theme and will be hard to resolve. Areas of concern include:

- Monitoring and control techniques and technology
- Contamination from infrastructure (servicing center, transportation system, storage facilities)
- Techniques for cleaning optical surfaces in space

EXHIBIT 7-6
KEY COMMUNICATIONS ISSUES AND TALL POLES

Commercial industry is driven by economics/risk.

Some technologies have potential economic risk/benefit:

- Automation and robotics
- LEO deployment and checkout
- Low-thrust OTV and GEO.

GEO platforms large aperture antennas are technology drivers:

- Assembly and construction
- Orbital checkout and demos
- OMV/smart front end
- Automation and robotics
- Low-thrust OTV to GEO
- GEO service.

Servicing functions required/desired early and continuing.

Automation and robotics applies across the board.

is driven primarily by economic considerations, including return on investment and risk associated with new technology; thus, the related systems tend to be designed using proven technology.

Despite the industry's unwillingness to push the state-of-the-art, the communications team felt that automation and robotics technology would provide a favorable economic risk/benefit ratio in selected areas. This technology would be particularly important in supporting deployment to low Earth orbit (LEO) and checking out communications satellites at the Space Station prior to final transit to geosynchronous orbit (GEO). The team also felt that low-thrust transfer to GEO would provide advantages by allowing predeployment of sensitive appendages and complex mechanical systems in LEO. Failure could be identified and rectified at the Shuttle or Space Station before GEO transfer, thus providing an added element of reliability.

The communications team identified the next generation of large aperture antennas, which will require on-orbit assembly, construction, and checkout, as primary technology drivers. The team felt that precursor demonstration flights to prove out new technology required for these missions would be an economically practical necessity. Automation and robotics was again seen as important in supporting assembly, maintenance, servicing, and checkout in the LEO environment. In addition, when coupled with cost-effective transportation systems, a mobile automation and robotics capability was seen as a desirable asset for remote servicing and other activities in both LEO and GEO.

Earth Observations

Exhibit 7-7 identifies the user mission/technology requirements for the Earth observations team. Massive amounts of data and high instrument data rates will drive both communications and data management technology. Significantly

EXHIBIT 7-7
TECHNOLOGY REQUIREMENTS FOR EARTH OBSERVATION MISSIONS

Area	Specifics	Task Equipment	When
Automation and Robotics	Telerobotics	Servicing attached payloads	IOC
		Assembly of large antennas	Med
	Telescience	Remote control of satellite Equipment	IOC
	Supervisory	Progressive shift from human to computer control	Med
	Functional Autonomy	Highly automated/integrated operations	Far
Communications	Bandwidth	Video transmission & high inst. data rates	IOC
	Time Delay	Events preview simulator	IOC
Data Management	High data rates	Enhanced TDRS transmission use	Far
	On-board processing	Fault tolerant processing/ high process rates	Far
	Mass data storage	On-board data storage for selected data dumps	IOC
Extravehicular Activity	High pressure suits	Assembly and servicing on station	IOC
Manned Systems	Monitor and Control	On-orbit workstation for attached payloads	IOC
Mechanisms	ORU Exchange	Special tools to interface manipulator to ORMS	IOC
	Contingency OPS	Unique tool set to adjust instrument set	Med
Power	High power supply	Power storage for quick energy pulse	IOC
Propulsion	Servicer Transporter-LEO	Low energy transporter for in situ servicing	IOC
	Satellite Transporter-GEO	Low-g orbit transfer capability	Far
	Servicer Transporter-GEO	High energy orbit transfer for in situ servicing	Far
Assembly	Assemble Large Antenna	Assembly/staging facility for deployment to GEO	Far
Servicing	S/C Serviceability	Module (ORU) exchange, optics cleaning fluid resupply, etc.	Med/Far

increased bandwidth and high-speed, high-capacity on-board processing and mass data storage will be required. In the assembly, maintenance, and servicing area, the team identified the need for a combination of automation and robotics technologies to be used with advanced high-pressure suits for extravehicular activity (EVA) in the IOC time frame. It also forecast a need for a progressive shift from human to computer control as the technology progresses. The ultimate objective would be system functional autonomy -- that is, highly automated/integrated operations with a minimal amount of human oversight or intervention.

Key issues and technology tall poles for Earth observations are presented in Exhibit 7-8. Among these, the team identified the need for technology to support in-space assembly and checkout of large antenna systems as particularly important. It also identified requirements for maintaining and servicing platforms and the availability of free-flyers in both LEO and GEO. Key automation and robotics technologies include development of knowledge bases and massive storage capability for expert systems, artificial intelligence, telescience, and teleoperation. The team also identified advanced technology needs for autonomous rendezvous and docking capabilities to support unmanned space servicing vehicles and systems for remote operations.

In situ environmental contamination, including outgassing, particulates, and electromagnetic interference were specified as an area of continuing concern to Earth observations. For man-made contamination, preventive measures for control at the source (via material selection or design practices) and cleaning and restoration measures will be required.

Mechanical motion was identified as another source of contamination. Both active and passive means of vibration

EXHIBIT 7-8
KEY EARTH OBSERVATION ISSUES AND TALL POLES

Advanced initiatives in earth observations will require new processes and capabilities for:

- On-orbit assembly, checkout and deployment of large antennas
- Long operational periods with provisions for scheduled servicing
- Platform servicing through ELVs

Automation and robotics will provide major benefits through progressive evolution of:

- Knowledge bases and expert systems
- Assembly and servicing of platforms (LEO and GEO), free-flyers and Space Station attached P/L (intelligent robotics)
- Telescience and teleoperation for greater cognitive operations

Contamination is a continuing concern. Solutions may include:

- Design for minimum contamination sources
- Techniques for collection and cleanup
- Design and isolation to reduce vibration

Key component and subsystem technologies include:

- Autonomous rendezvous and docking of elements
- Cryogen resupply for thermal cooling with possible act, thermal control
- Subsatellite operations from station
- Massive storage capability of archieval data with quick access

control, base motion compensation, and sensor isolation techniques were endorsed as highly needed near-term technologies.

Lunàr and Planetary

The lunar base or manned Mars missions will require advanced technologies. Manned systems will be needed that exceed the performance capabilities of technologies currently in the research stage. The technology discipline requirements listed in Exhibit 7-9 indicate the wide range of technological advances needed to enable such missions. Many of these technologies will probably be pursued on the Space Station in its role as a user facility. However, the technology areas requiring significant performance increases or fundamentally new systems will require special attention.

Exhibit 7-10 condenses the many lunar/planetary technology needs to a few critical requirements or tall poles. These are the areas where radically new approaches or concepts are needed.

An underlying critical requirement is transportation -- low-cost access to LEO and a space-based orbital transfer vehicle (OTV) that can go to lunar orbit. A second underlying critical requirement is for a spaceport or "shipyard" function at the Space Station. Staging areas should be provided for assembly, vehicle servicing, and propellant transfer and storage. The activities of this function will increase with the number of lunar and planetary missions. Eventually, this function will consume most of the station's resources, and the resulting dynamic disturbances will interfere with other station uses.

A third critical technology requirement for lunar and planetary missions is ecosystems technology. Physiological (human) and biological (plants and animals) studies will be

EXHIBIT 7-9
TECHNOLOGY REQUIREMENTS FOR LUNAR AND PLANETARY MISSIONS

DISCIPLINE AREA	FUNCTIONAL REQUIREMENTS	TECHNOLOGY REQUIREMENTS
ATTITUDE CONTROL & STRUCTURES	Rotating/revolving systems Proximity operations Large structure dynamics and stability	Dynamics and control laws Rendezvous and docking Sensors and communication Instrumented space station
AUTOMATION & ROBOTICS	Automated systems Rendezvous & docking Experiment assembly Servicing	Spaceborne symbolic processors Self test and repair Manipulators Telerobotics Planning/scheduling/diagnostics
DATA MANAGEMENT	Autonomous operation	High capacity random access memories Artificial intelligence Knowledge capture Analysis and preprocessing High bandwidth networking & protocols
LIFE SUPPORT	Closed life support systems	Oxidation processes Physical/chemical systems Biological systems Waste processing Food production
EXTRAVEHICULAR ACTIVITY	Life support systems Capability	Versatile, multiple application portable life support systems Space-based, rechargeable kinesthetics
FLUID MANAGEMENT	Propellant storage & transfer	Cryogenic fluid management Gauging; instrumentation Fluid connectors

EXHIBIT 7-9
(CONTINUED)

DISCIPLINE AREA	FUNCTIONAL REQUIREMENTS	TECHNOLOGY REQUIREMENTS
MANNED SYSTEMS	Biomedical Long term physiological Medical/dental clinic Behavioral science Crew systems	Pharmacology, nonintrusive & intrusive Variable gravity Instrumentation Procedural techniques Trash processing
MATERIALS	Extraterrestrial materials processing Radiation protection	Refurbishable thermal control surfaces Simulated lunar gravity Very low gravity processing Construction technology Shielding for high energy particles, radiation Sensors Polar platform
MECHANISMS	Rotating/revolving systems	Moving interfaces Fluid connectors
POWER	Power transfer to vehicles Manned vehicles	Regenerable power systems Robotics Nuclear power systems Power transport Power storage (superconducting)
PROPULSION	Planetary spacecraft Space-based launch Spin/despin Lunar vehicles	Low thrust engines EVA maneuvering Propellant storage & transfer Auxiliary propulsion Engines (ferry, translunar vehicle, surface)
STRUCTURES	Rotating/revolving systems Assembly - checkout	Tethers; Centrifuges Hangars; Robotics "Strong-back" large structures In situ fabrication

EXHIBIT 7-9
(CONTINUED)

DISCIPLINE AREA	FUNCTIONAL REQUIREMENTS	TECHNOLOGY REQUIREMENTS
THERMAL	Thermal management (deep space) Fire control	Radiator/rejection Utilization "Instrumented space station"
ASSEMBLY	Large structures Experiments	Structural modularization Very large scale construction (antenna & aerobrake classes)
SERVICING	Lunar ferry Portable life support sys. Maintenance & repair	Servicing bay Regenerable air & thermal Long life systems Fix-it workshop
ECOSYSTEMS	Planetary quarantine facility CELSS Lunar agriculture Smoke & chemical containment Biological contaminants Plant/animal biosystem	Isolation Biosystem support Horticulture (low gravity) Sensors Rapid air revitalization
AUTONOMOUS SYSTEMS	Long life reliability & maintainability Self-diagnosis & repair	Real time Artificial intelligence Radiation tolerant system
REMOTE PLANETARY OBSERVATIONS	Telescopes Precursor missions Communications Planetary science	Large scale assembly Maintenance

EXHIBIT 7-10
KEY LUNAR AND PLANETARY MISSION
ISSUES AND TALL POLES*

TRANSPORTATION

- Low cost, high capacity ETO access
- Space-based OTV (with lunar orbit capability)

SPACEPORT OPERATIONAL MODE FOR SPACE STATION

- Assembly, checkout, and staging
- Refueling and propellant storage
- Maintenance and servicing of planetary vehicles

ECOSYSTEMS OPERATION

- Closed life support
- Variable-g capability (man-rated)
- Plant and animal biosystems

ROTATING/REVOLVING SYSTEMS

- Variable-g capability (science and technology)
- Impacts all disciplines

LONG-LIFE AUTONOMOUS OPERATION

*Requirements are for experiments onboard the Space Station needed. Plants must be developed for lunar agriculture. Facilities must be available to quarantine planetary spacecraft and returned samples. Completely closed life support systems will be needed, perhaps using plants for air regeneration and food production as well as waste processing.

A fourth critical requirement is for artificial gravity systems. Humans in prolonged zero gravity (more than 6 months), may undergo unacceptable physiological changes, such as calcium loss from bones. If these cannot be countered through exercise or pharmacology, long-duration spaceflight may require rotating or revolving systems to provide artificial gravity. Virtually all technology disciplines will be affected by such systems -- fluid management, communications, proximity operations, structures, and mechanisms. Centrifuges or tethered systems will be required to conduct physiological tests and planetary agriculture and materials processing experiments. These systems will also have a profound impact on station operations.

A fifth critical technology requirement is for long-life autonomous operation of lunar and planetary systems. Mission systems must remain reliable and maintainable for years. Real-time expert systems will be needed for self-diagnosis and repair, contingency planning, and scheduling. All systems must be radiation tolerant.

Microgravity

The microgravity team represented materials processing, physics and chemistry, and life sciences missions. Technology needs for these fields were defined along classical engineering disciplines, as shown in Exhibit 7-11. In the case of materials processing, the technology requirements center on the need to sustain a perturbation-free microgravity environment. Life sciences technology requirements center on research to determine

EXHIBIT 7-11
TECHNOLOGY REQUIREMENTS FOR MICROGRAVITY MISSIONS

Attitude Control

CG Management

Automation & Robotics

Robotics/teleoperated facility
Telescience
Automated production
Animal maintenance
Process materials management
Automated fecal analysis

Communications

Voice stress analysis
Real-time, high-resolution television

Data Management

Expert systems/human resources
Accelerometers (real-time broad band)
High-resolution IR camera

ECLSS

CELSS
Contamination monitoring and control
Fire detection and control

EVA

Hard suit, soft gloves

Fluid Management

Transfer and storage
Process materials management
Liquid/vapor transfer
"Spill" cleanup

EXHIBIT 7-11
(CONTINUED)

Manned Systems

Dedicated crew training facility
Productivity measurement and enhancement
Workload evaluation and appropriation
Interactive group dynamics
Variable G R&R facility
Physiological countermeasures
Emergency medical care

Materials

Automated on-orbit characterization
Automated structure manufacturing
Improved materials qualifications
Disposable animal habitat liners
Decor materials technology
Window protection
Radiation shielding by secondary structures

Mechanisms

Vibration/EMI/acoustic isolation
Soft docking

Power

Nuclear power
Portable shielding

Structures

4m centrifuge
Tethers
Man-rated centrifuge (VGRF)
Manned OMV

Assembly

Integration and verification
On-orbit assembly of centrifuge and balancing

Servicing

Low-cost rapid sample return
EVA support for on-orbit c/o and resupply
Automated inventory control

EXHIBIT 7-11
(CONTINUED)

Space Facilities

Toilets that work
Superconducting magnets
High temperature furnaces
Variable-G R&R facilities
Habitat modularization
Holographic communications
Electric propulsion
Showers
Advanced MMU

the effects of reduced gravity environments on the biological functions of plants, animals, and humans. The more critical technologies identified by this team are presented in Exhibit 7-12.

The microgravity processing scenarios foresee an evolution from initial research activities through pilot production to full-scale commercial factories. The technology associated with this trend will include increased application of automation and robotics, more power-intensive operations, and efficient and safe materials handling systems.

Resisto-jets for drag make-up, vibration isolation systems, and soft docking techniques were identified as requirements for maintaining the low-gravity environment. These technologies were integrated with man-operated free-flying production facilities, including highly automated labs and experiments and process controls requiring minimal human involvement. Associated technology for hazardous material and waste product handling included techniques for isolation, quarantine, and disposal. Automated logistics systems will be required for supply, inventory, and distribution of raw and processed materials.

As materials processing operations mature, the technology for power production will progress from multihundred kilowatt thermoelectric and solar dynamic systems to megawatt SP-100 class nuclear power reactors for full-fledged factories.

The life sciences community views the Space Station as an experimental facility. Therefore, technologies associated with low- and variable-gravity research and applied automation were identified. Centrifuges of various sizes and gravity levels, plant and animal vivariums, and techniques for rapid sample

EXHIBIT 7-12
KEY MICROGRAVITY ISSUES AND TALL POLES

Automation and Robotics

Robotic/teleoperated facility
Telescience
Automated production
Animal maintenance
Process materials management
Automated fecal analysis

Manned Systems

Dedicated crew training facility
Productivity measurement and enhancement
Workload evaluation and appropriation
Interactive group dynamics
Variable R&R facility
Physiological countermeasures
Emergency medical care

Mechanisms

Vibration/EMI/acoustic isolation
Soft docking

Power

Nuclear power (1 megawatt and greater)
Portable shielding

Communications

Voice stress analysis
Real-time, high resolution televisions

return, bioisolation quarantine, and analysis were felt to be some of the more important areas for technology development.

In addition to pure research on the effects of gravity on living species, life sciences activities will focus on the productivity of humans in space, with emphasis on preparations for extended-duration occupancy. Technology needs were identified in the areas of crew performance and training, group dynamics (including psychological countermeasures), biomedical research and medical care, and overall human acclimation to zero gravity. Technology for fully closed ecological systems will also be needed for long-duration missions.

SUMMARY

The highest priority enabling technologies (tall poles) identified by each team are presented in Exhibit 7-13. Using this matrix, recurrent themes can be identified across the different mission teams, and trends can be seen within and between the individual discipline technologies. These themes are summarized in Exhibit 7-14.

Large precision and controllable structures and capabilities for assembly and servicing are common requirements for astronomy and astrophysics, communications, and Earth observation. Manned systems technologies are needed for Earth observation, lunar and planetary, and microgravity missions: mechanisms technology will be required for gravity effects in the latter two fields. Automation and robotics was the most called for technology for a variety of reasons: productivity improvement, cost benefit, and elimination of human involvement. Technology to prevent, detect, control, and recover from contamination is needed for missions in the LEO environment.

Space experimentation was also identified as a broadly required function to prove out and complete technology development. Activities included the more generic aspects of discipline research and technology and full demonstration of system and mission performance. The teams also identified many predevelopment and preoperation activities that would use the Space Station as a test bed before actual mission design and development.

Proper execution and timing of technology development programs can enable missions and facilitate Space Station evolution. Some technologies may help resolve conflicting mission requirements. If properly designed into the Space Station systems, these could have favorable performance and economic impacts on branching and the overall evolution program.

EXHIBIT 7-13
HIGH-PRIORITY AND ENABLING TECHNOLOGIES

USER TEAMS	ATTITUDE CONTROL STABILITY	AUTOMATION & ROBOTICS	COMMUNICATION	DATA MANAGEMENT	ENVIRONMENTAL CONTROL & LIFE SUP.	EXTRAVEHICULAR ACTIVITIES	FLUID MANAGEMENT	MANNED SYSTEMS	MATERIALS	MECHANISMS	POWER	PROPULSION - OTV	STRUCTURES	THERMAL	ASSEMBLY	SERVICING	FACILITIES/MODULES/SYSTEMS	CONTAMINATION
ASTRONOMY & ASTROPHYSICS		●										●	●		●	●		○
COMMUNICATIONS													●		●	●	●	
EARTH OBSERVATION		●		●				●					●			●		●
LUNAR AND PLANETARY		●			●			●		●								
MICROGRAVITY		●	●					●		●	●							○

EXHIBIT 7-14
KEY TECHNOLOGY REQUIREMENTS AND OBSERVATIONS

Transportation is enabling.

Mission pervasive items drive many technologies:

- Large structures
- Automation and robotics
- Manned systems
- Contamination

Experimentation covers broad spectrum:

- In space R&T.
- Demos
- Predevelopment
- Preoperations

Test Bed

Technology influence:

- Enabling missions and evolution scenarios
- "Conflict" resolutions
- "Branch" delay at some threshold

APPENDIX A

SPACE STATION EVOLUTION WORKSHOP II
PARTICIPANTS LIST

SPACE STATION EVOLUTION WORKSHOP II
Participants List

Mr. Theodore Aepli — Team E
Space Station Program Manager
General Electric Company
P. O. Box 8555
Building 11, Room 1121
Philadelphia, PA 19101
FTS 215-354-3870

Mr. John Anderson — Team L
Large Space System Technology
Code RS
National Aeronautics and Space Administration
Washington, DC 20546
FTS 453-2756

Lieutenant Colonel Joseph Angelo — Team M
AFTAC/TXO
Chief of Electro-Optic Systems Division
Air Force Technical Applications Center
Patrick AFB, FL 32925
(305) 494-5853

Mr. Ray Arnold — Team E
Deputy Director
Earth Sciences and Applications Division
Code EE
Office of Space Science and Applications
National Aeronautics and Space Administration
Washington, DC 20546
FTS 453-1181

Ms. Barbara S. Askins — Team F
Code SED
Advanced Design and Development Branch
Office of Space Station
National Aeronautics and Space Administration
Washington, DC 20546
FTS 453-1177

Mr. Richard F. Baillie — Team CS
Code KC2
Technical Discipline Manager for Configuration
Johnson Space Center
National Aeronautics and Space Administration
Houston, TX 77058
FTS 525-5491

Mr. Gerry Barna
Chief of Advanced Programs and Planning Office
Code 501-15
Lewis Research Center
National Aeronautics and Space Administration
2100 Brookpark Road
Cleveland, OH 44135
FTS 297-5308

Team L

Dr. Chris Baumgart
AFTAC/TXE
Radiation Physicist
Patrick AFB, FL 32925-6001

Team E

Mr. Gene Beam
Manager, Project Integration
Code KA11
National Aeronautics and Space Administration
Marshall Space Flight Center, AL 35812
FTS 824-1755

Team CS

Mr. Marc Bensimon
Chief, Systems Management Engineering Branch
Code SEG
Office of Space Station
National Aeronautics and Space Administration
Washington, DC 20546
FTS 453-2386

Team CS

Dr. David Black
Chief Scientist
Code SC
Office of Space Station
National Aeronautics and Space Administration
Washington, DC 20546
FTS 453-2370

Team F

Dr. B. J. Bluth
Human Productivity Branch
Code SEM
Office of Space Station
National Aeronautics and Space Administration
Washington, DC 20546
FTS 453-2379

Team M

Dr. Harold S. Braham
Manager of Advanced Comsats
TRW, Space Communications Division
One Space Park
Redondo Beach, CA 90278
(213) 535-3196

Team C

Ms. Karen D. Brender — Team CS
Evolutionary Definition Office
Space Station Office
Mail Stop 288
Langley Research Center
National Aeronautics and Space Administration
Hampton, VA 23665
FTS 928-4826

Mr. John V. Brown — Team C
Manager of Systems Engineering Laboratory
Ford Aerospace Communications Corporation
Mail Stop G77
3939 Fabian Way
Palo Alto, CA 94303
(415) 852-4050

Mr. Jim Burke — Team L
Jet Propulsion Laboratory
Mail Stop 180-703, Section 940
National Aeronautics and Space Administration
4800 Oak Grove Drive
Pasadena, CA 91109
FTS 792-6363 or (818) 354-6363

Mr. John Butler — Team I
Chief of Orbital Support Systems Group
Program Development, Code PS04
National Aeronautics and Space Administration
Marshall Space Flight Center, AL 35812
FTS 824-4833

Dr. S. Joseph Campanella — Team C
Vice President and Chief Scientist
COMSAT Laboratories
22300 Comsat Drive
Clarksburg, MD 20871
(301) 428-4257

Mr. Louis Cuccia — Team C
Manager of Advanced Planning
Code EC, Communications Division
National Aeronautics and Space Administration
Washington, DC 20546
FTS 453-1505

Mr. Dordain
European Space Agency — Team M
8 - 10 rue Maris Nikis
75738 Paris CEDEX 15
FRANCE
33-1-42737338

Mr. Gilbert S. Drucker — Team M
Systems Engineering and Integration
Space Station Power Engineering
Mail Stop LA19
Rocketdyne Division of Rockwell International
6633 Canoga Avenue
Canoga Park, CA 91303
FTS 983-4322

Mr. C. David Eakman — Team CS
Manager of Space Station and ADP Systems
McDonnell Douglas Astronautics Company
Washington Operations Division
2092 Gaither Road
Rockville, MD 20850
(301) 670-7900

Mr. Robert E. Edelson — Team L
Manager of Orbital Operations
Code SO
Office of Space Station
National Aeronautics and Space Administration
Washington, DC 20546
FTS 453-2783

Mr. Ken Frost — Team A
Code 600.2
Goddard Space Flight Center
National Aeronautics and Space Administration
Greenbelt Road
Greenbelt, MD 20771
FTS 286-8824

Dr. Christ Ftaclas — Team A
Astrophysicist
Space Science Division
MS-897
Perkin Elmer
100 Wooster Heights Road
Danbury, CT 06810
(203) 797-6448

Mr. Adam Gruen — Team F
Project Historian
Space Station History Project
Code LBH
National Aeronautics and Space Administration
Washington, DC 20546
FTS 453-8757

Dr. Herbert Gursky
Superintendent, Space Sciences Division
Naval Research Laboratory
Washington, DC 20375
(202) 767-6343

Team A

Dr. Richard E. Hartle
Assistant Division Chief
Laboratory for Atmosphere
Code 610
Goddard Space Flight Center
National Aeronautics and Space Administration
Greenbelt Road
Greenbelt, MD 20771
FTS 286-8234

Team E

Dr. Michael Hayes
Project Manager Systems Engineering and Operations
12214 Lakewood Blvd.
Rockwell International
Downey, CA 90241
(213) 922-4419

Team A

Mr. Missak M. Herardian
Program Manager, Geostationary Platform Program
Astronautics Division
Lockheed Missiles and Space Company
Organization 57-03, Guilding 529
P. O. Box 3504
Sunnyvale, CA 94088-3504
(408) 742-4819

Team C

Mr. John H. Hill
Manager, Technology Assessment
Advanced Development
Space Station Programs
McDonnell Douglas Astronautics Company
5301 Bolsa Avenue
Huntington Beach, CA 92647
714-896-4317

Team A

Dr. Earle K. Huckins, III
Deputy Manager, Evolutionary Definition Office
Space Station Office
Mail Stop 288
Langley Research Center
National Aeronautics and Space Administration
Hampton, VA 23665
FTS 928-4830

Team C

Dr. Tak Kato
Code PA 121
NASDA - Houston Liaison Office
Johnson Space Center
Houston, TX 77058
(713) 483-3410

Team C

Dr. Paul W. Keaton
Physicist
Los Alamos National Laboratory
Los Alamos, NM 87545
FTS 843-9985

Team L

Dr. J. Richard Keefe
Discipline Scientist
Life Sciences - Space Station
Code EBF
National Aeronautics and Space Administration
Washington, DC 20546
FTS 453-1525

Team M

Mr. Robert M. Keller
Staff Manager
Systems Engineering and Integration
McDonnell Douglas
Mail Stop 11-3
5301 Bolsa Blvd.
Huntington Beach, CA 92647
(714) 896-2928

Team M

Mr. Karl Knott
European Space Agency
ESTEC
KEPLERLANN 1
Noordwijk, HOLLAND
317-719-83597

Team E

Mr. Herbert R. Kowitz
Evolutionary Definition Office
Space Station Office
Mail Stop 288
Langley Research Center
National Aeronautics and Space Administration
Hampton, VA 23665
FTS 928-4830

Team C

Mr. George F. Lawrence
Evolutional Definition Office
Mail Stop 288
Langley Research Center
National Aeronautics and Space Administration
Hampton, VA 23665
FTS 928-4830

Team A

Dr. Thomas Labus — Team M
Chief, Advanced Program Development Branch
Code 501-15
Lewis Research Center
National Aeronautics and Space Administration
21000 Brookpark Road
Cleveland, OH 44135
FTS 297-5294

Dr. William Lenoir — Team CS
Principal, Space Systems Practice
Booz, Allen & Hamilton
4330 East-West Highway
Bethesda, MD 20814
(202) 951-2285

Mr. Bruce LeRoy/U3217 — Team C
Technical Staff Engineer
General Electric
Space Systems Division
P.O. Box 8555
Philadelphia, PA 19101
(215) 354-2843

R. Robert L. Lohman — Team CS
Technical Advisor, Policy and Plans Division
Code SP
Office of Space Station
National Aeronautics and Space Administration
Washington, DC 20546
FTS 453-2399

Mr. Julius B. Lovell — Team E
Code PB1
Johnson Space Center
National Aeronautics and Space Administration
Houston, TX 77058
FTS 525-2741

Dr. Henry Lum — Team C
Chief, Information Sciences Office
Mail Stop 244-7
Ames Research Center
National Aeronautics and Space Administration
Moffett Field, CA 94035
FTS 464-6544

Dr. Wendell W. Mendell
Senior Space Scientist
Code SN3
Johnson Space Center
National Aeronautics and Space Administration
Houston, TX 77058
FTS 525-2956

Team L

Mr. Barry Meredith
Space Station Office
Mail Stop 288
Langley Research Center
National Aeronautics and Space Administration
Hampton, VA 23665
FTS 928-4830

Team E

Dr. Donald Miller
Chief, Satellite Applications Laboratory
NOAA/NESDIS E/RA2
World Weather Building
Washington, DC 20233
FTS 763-8282

Team E

Dr. Sundaram Moorthy
Supervisor, Satellite and Special Services Planning
AT&T Bell Laboratories
Crawfords Corner Road
Holmdel, NJ 07733
(201) 949-6649

Team C

Dr. Dietrich Muller
Professor of Physics
University of Chicago
933 East 56th Street
Chicago, IL 60637
(312) 962-7846

Team A

Mr. Robert F. Murray
Space Station Office
Mail Stop 288
Langley Research Center
National Aeronautics and Space Administration
Hampton, VA 23665
FTS 928-4830

Team L

Dr. Ichiro Nakatani
Associate Professor
The Institute of Space and Astronautical Science
c/o R. S. Tatum
ISTP Project Manager
Goddard Space Flight Center
National Aeronautics and Space Administration
Greenbelt, MD 20771
(301) 286-3178

Team A

Dr. Robert J. Naumann
Chief Space Station Scientist
Code ES71
National Aeronautics and Space Administration
Marshall Space Flight Center, AL 35812
FTS 824-7755

Team H

R. Ralph W. Nicholls
Distinguished Research Professor of Physics
Director, Centre of Research in Experimental Space Science
4700 Keele Street
Downsview, Ontario M3J1P3
CANADA
(416) 736-5247

Team A

Mr. John Niehoff
Manager, Space Science Department
Science Applications International Corporation
One Woodfield Place Building
1701 E. Woodfield Road, Suite 819
Schaumburg, IL 60179
FTS 353-2227

Team L

Mr. Peter Norris
Executive Vice President
EOSAT
4300 Forbes Blvd.
Lanham, MD 20706
(301) 522-0515

Team E

Mr. Robert E. Pace, Jr.
Vice President
Microgravity Research Associates, Inc.
P. O. Box 12426
Huntsville, AL 35802
(205) 539-0781

Team M

Dr. Laurence Peterson
Assistant Director, Astrophysics Division
Code EZ
National Aeronautics and Space Administration
Washington, DC 20546
FTS 453-8547

Team A

Mr. Kent Price
Principal Engineer
Ford Aerospace Communication Corporation
Mail Stop G83
3939 Fabian Way
Palo Alto, CA 94303
(415) 852-6179

Team C

Mr. E. Brian Pritchard
Manager, Evolutionary Definition Office
Space Station Office
Mail Stop 288
Langley Research Center
National Aeronautics and Space Administration
Hampton, VA 23665
FTS 928-4830

Team CS

Mr. William Ramage
Customer Accommodations
Code KA31
National Aeronautics and Space Administration
Marshall Space Flight Center, AL 35812
FTS 824-1882

Team M

Mr. James R. Ramler
Chief, Space Communications Division
Mail Stop 54-1
Lewis Research Center
National Aeronautics and Space Administration
21000 Brookpark Road
Cleveland, OH 44135
(216) 433-3475
FTS 297-3475

Team C

Mr. Pat Rawlings
Art Director
Eagle Engineering, Inc.
Suite 315
711 Bay Area Blvd.
Webster, TX 77598
(713) 338-2682

Team F

Dr. Robert Ried
Manager, Advanced Programs Office
Code ED
Johnson Space Center
National Aeronautics and Space Administration
Houston, TX 77058
FTS 525-2258

Team L

Mr. William Roberts
Mail Stop PS02
National Aeronautics and Space Administration
Marshall Space Flight Center, AL 35812
FTS 824-0621

Team E

Mr. J. Glen Rumbold, M.Sc — Team M
Space Division
National Research Council
Montreal Road
Ottawa KIAOR6
CANADA
(613) 993-2113

Mr. Ole Smistad — Team M
Code PD2
Johnson Space Center
National Aeronautics and Space Administration
Houston, TX 77058
FTS 525-6426

Dr. O. Glenn Smith — Team L
Manager, Science Integration and Requirements
Synthesis Office
Space Station Program Office
Code PD3
Johnson Space Center
National Aeronautics and Space Administration
Houston, TX 77058
FTS 525-6541

Mr. Richard A. Spencer — Team E
Space Station A&R Manager
Martin Marietta
P. O. Box 179, Mail Stop D-1744
Denver, CO 80201
(303) 971-5681

Dr. Rudolf A. Stampfl — Team C
Manager, Advanced Missions
RCA Astro-Electronics
P. O. Box 800
Princeton, NJ 08540
(609) 426-2551

Mr. James Michael Stevens — Team E
Manager, Space Station Operations
Code TX
National Aeronautics and Space Administration
Washington, DC 20546
FTS 453-2030

Mr. William Stoney — Team A
Manager, Advanced Development
Mail Stop 101
RCA Astro-Electronics
P. O. Box 800
Princeton, NJ 08540
(609) 426-3401

Mr. Richard Storm
Manager, Space Safety, Reliability, and
Quality Assurance
Code DE
National Aeronautics and Space Administration
Washington, DC 20546
FTS 453-1866

Team A

Mr. David Suddeth
Systems Requirements Manager
Space Station Project
Code 400.6
Goddard Space Flight Center
National Aeronautics and Space Administration
Greenbelt Road
Greenbelt, MD 20771
FTS 888-1866

Team E

Dr. Katheryn D. Sullivan
NASA Mission Specialist
Code CB
John Space Center
National Aeronautics and Space Administration
Houston, TX 77058
FTS 525-2221

Team CS

Mr. Lee Tilton
Special Assistant to the Director for Advanced
Programs
Code MT
National Aeronautics and Space Administration
Washington, DC 20546
FTS 453-1156

Team CS

Mr. William Tumulty
Chief, Advanced Design and Development Branch
Code SED
Office of Space Station
National Aeronautics and Space Administration
Washington, DC 20546
FTS 453-2391

Team C

Dr. Deene J.Weidman
Evolutionary Definition Office
Space Station Office
Mail Stop 288
Langley Research Center
National Aeronautics and Space Administration
Hampton, VA 23665
FTS 928-4830

Team A

Mr. Charles Weyandt — Team C
Ford Aerospace Communications Corporation
Mail Stop G-80
3939 Fabian Way
Palo Alto, CA 94303

Dr. Phillip C. Wheeler — Team A
TRW
Mail Stop R5-2030
One Space Park
Redondo Beach, CA 90278
(213) 536-4552

Dr. Harvey Willenberg — Team M
Manager, Space Science Accommodations
Boeing Aerospace Company
P. O. Box 1470
Mail Stop JA70
Huntsville, AL 35807-3701

Dr. Gregory Wilson — Team E
Deputy Director, Atmospheric Sciences Division
Code ED41
National Aeronautics and Space Administration
Marshall Space Flight Center, AL 35812
FTS 824-1646

Mr. Gordon Woodcock — Team L
Laboratory Module Outfitting Manager
Boeing Aerospace Company
P. O. Box 1470
Mail Stop JA-85
Huntsville, AL 35807
(205) 461-2396